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# Action protocols for seismic evaluation of structures and damage restoration of residential buildings in Andalusia (Spain): "IT-Sismo" APP

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**Abstract:** The seismotectonic conditions of the Iberian Peninsula trigger the occurrence of earthquakes with an occasional periodicity, but with intensities greater than VI on the European macroseismic scale (EMS). For this reason, local action protocols are required in order to efficiently organise the technical inspections that must be carried out on a massive scale after events such as the earthquakes experienced in the Spanish cities of Lorca (2011) and Melilla (2016). This paper proposes the development of a set of documents for the evaluation and diagnosis of the state of existing buildings and infrastructure regarding seismic activity in Andalusia. With special attention paid to residential typology, approximations have been carried out to the normative context, to general comparatives, to particular analyses of a case studies selection, and to complementary approaches. The results have led to the establishment of two specific protocols. Firstly, the short-term guideline enables the classification of damage and risk levels, and the determination of what immediate interventions should be carried out through the generation of a preliminary on-site report. This activity can be performed by architects and engineers with the help of a mobile-device application (APP IT-Sismo Andalucía). Additionally, a long-term protocol provides calculation procedures and constructive solutions for the improvement of the seismic behaviour of affected buildings. Specially designed tests demonstrate the validity of the protocols and illustrate the need for information and communication technologies (ICT) tools in the evaluation of architectonic technical aspects.

**Keywords:** mobile-device applications; automatic protocols; damage assessment; in situ structural diagnosis; seismic restoration

## 1. Introduction

The seismotectonic conditions of the Iberian Peninsula provoke the intermittent occurrence of earthquakes with intensity values higher than IV on the European macroseismic scale (EMS) [1]. Within this geographic framework, the autonomous community of Andalusia presents especially high risk values in the areas linked to the mountain ranges of the Baetic system (Sierra Bética). This issue can be checked analysing the earthquake recurrence data in this area [2,3], which is one of the most populated regions in Spain with more than eight million inhabitants and an area close to 90,000 km$^2$.

In this respect, the unfortunate consequences of this type of seismic event have been experienced in recent years in populations very close to the Andalusian territory. In 2011, the city of Lorca, located in the border region of Murcia, suffered the effects of an earthquake of magnitude 5.1 and intensity VII (EMS), while in 2016, the city of Melilla, located on the African continent, suffered an earthquake of magnitude 6.3 that was felt with intensity III (EMS). In the specific case of Lorca, there were nine deaths, 310 injuries, and more than a thousand damaged buildings. Moreover, it should be borne in mind that the damage resulting from construction deficiencies, mainly landslides, were greater than the damage caused by structural failures in the affected buildings [4,5]. The earthquake that occurred in Melilla left no fatalities, but the constructive damage experienced was nevertheless very high [6–8]. In both cases, residential buildings constituted an architectural type especially affected by seismic events, which, in Andalusia, pose a threat to an estimated four million homes [9].

In the Portuguese territories closest to the Andalusian region, there is also a clear scenario of vulnerability to earthquakes. In this context, various studies have been developed for the evaluation of the seismic vulnerability of buildings located in urban centres, such as Faro, Lisbon, Coimbra, and Oporto. Such studies have shown that certain areas with a relatively low hazard level can present a high seismic risk due to a lack of maintenance of their buildings and to recent restoration interventions that increase the possibility of suffering damage from a seismic phenomenon [10–12].

Based on the aforementioned circumstances, the implementation of strategies to raise awareness both of the public and of public administrations regarding seismic events should be considered a priority task. This work is crucial not only for suitable decision-making, but also for raising awareness of the scope of repercussions caused by a relevant seismic event [13]. In this respect, in 2009, the Emergency Plan for Seismic Risk in Andalusia [14] was published at a regional level. Additionally, the seismic hazard map of the province of Malaga [15] at the provincial and local level, and the Municipal Action Plans for the seismic risk of Granada [16] and Benalmádena [17] have been published. These documents mainly focus on risk-reduction strategies, on the detection of the most highly vulnerable areas, and on planning for seismic damage scenarios through the adoption or proposal of specific procedures. These documents include a series of recommendations for people on how to proceed in the event of an earthquake and, in certain cases, they provide brief indications in order to perform a preliminary assessment of the damage and risks produced, and information regarding the safety measures to be employed.

These documents clearly show the growing concern of technicians and local authorities regarding the ever-present lack of seismic protection at both regional and local levels. Therefore, specific action protocols still need to be established for those technicians and citizens who can contribute towards the evaluation of the scope and the real risks of damage caused after the occurrence of a seismic event. This type of document is not only aimed at ensuring the safety of users, but also at detecting high-risk situations when carrying out technical inspections, in which professionals are exposed to aftershocks and to the existence of constructive elements that are in a state of unstable equilibrium. In this regard, at the regional level and in the period between 2006/2007, the project titled SISMOSAN, an assessment of the seismic hazard and risk in Andalusia [18] was developed. Subsequently, the authors of this article carried out a research project funded through a public call for bids, under the title "Seismic standard: Preliminary analysis and restoration in the face of damage to existing buildings and infrastructures". On completion of said project, a phase of testing and adjustment of the results was carried out, based on the digital tools generated within the framework of the aforementioned work.

Through this project, the design of a set of action guidelines has been analysed in greater depth. In a complementary and coherent way, these guidelines are aimed at expediting not only the mechanisms of technical and citizen mobilization in anticipation of future seismic events of relevant intensity that may occur in the Andalusian area, but also any measures for immediate action. Although these procedures could be applied in a general way to any building type, the tools developed are used for the evaluation of residential buildings, which are highly representative at a quantitative level. Therefore, specific aspects related to the use, typology and construction have been considered, within such a broad theme as that of housing.

In this way, this proposal develops a protocol for the evaluation and diagnosis after an earthquake of the Andalusian residential stock. All the planned tasks have been carried out through the application of procedures validated by the main international institutions in this field. At the same time, as a measure of methodological innovation, an interactive validation instrument is provided in the form of an application for mobile devices (APP), which, based on the use of information and communication technologies (ICT), favours decision-making by architects and engineers not specialized in seismic issues. In this way, the developed APP enables the post-catastrophe evaluation sheets to be filled out interactively and provides a preliminary automated diagnosis based on the information supplied by the technicians who supervise the properties affected by a seismic event.

This question is of major interest since, from the requirements demanded in each normative update, degrees of seismic behaviour can be inferred from certain groups of residential types in a general way, and therefore common technical and constructive aspects can be established in the analysis of the buildings.

The aim of this paper is to present a security needs assessment protocol to evaluate residential building after an earthquake, using a two-step procedure depending on the complexity of the situation, the availability of resources, and the size of the affected area. In a first step, a general survey would be carried out to assess the main damages, based on the technician's observations, and if it is needed; in a second step, a detailed analysis can be performed, which is usually more time-consuming. This document is especially focused in the development of the first step of the analysis.

## 2. Methodology and resources employed

By means of a structure of contents that enables the creation of a set of documents capable of responding to the complexity of the proposed objectives, the following lines of study and analysis have been developed in parallel (Figure 1): normative approximation and international guidelines, principal methods of evaluation, context conditions, general characteristics of Andalusian residential construction, and representativeness of the case studies. To this end, a multidisciplinary work team has been formed, mainly composed of architects and civil engineers. Furthermore, the most representative contents have been structured in an application for mobile devices, which is destined to function as an interactive guide for the use of the newly established protocols. For this purpose, a team of computer engineers has created a computer application based on the structure proposed by the work team, which will be discussed in Section 3.1.1. All this has led to the development of research, which, through a holistic and generalist approach, has addressed numerous issues by establishing a broad view of the problem at hand, and has contributed towards the progressive improvement of the current situation through the use of various approaches and complementary perspectives.

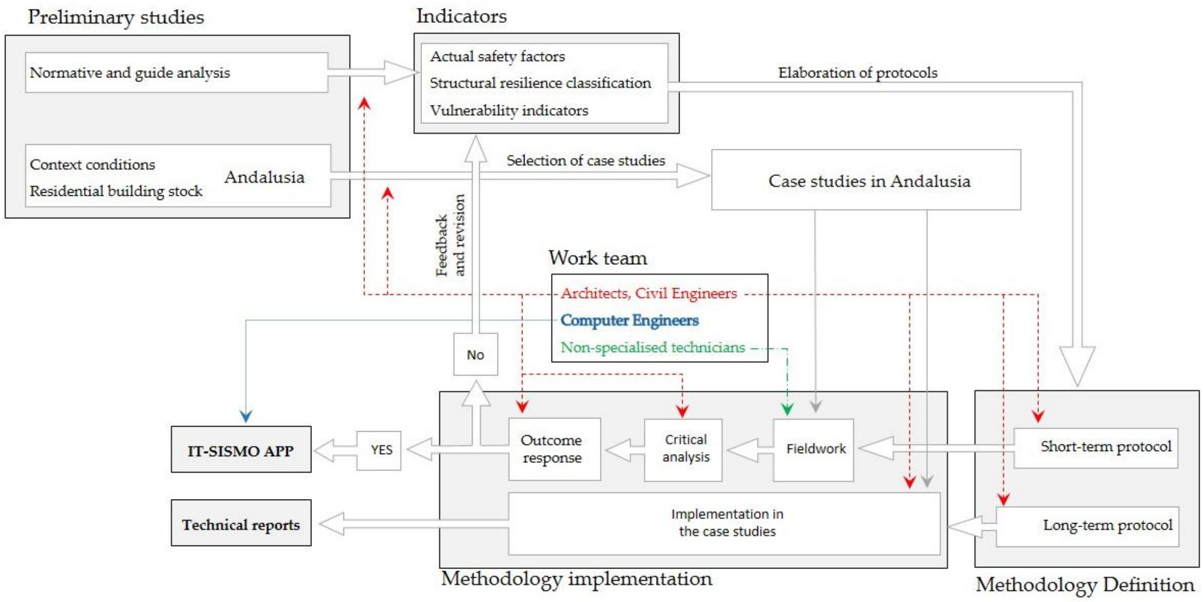


**Figure 1.** General outline relative to the development of the methodology of the present research. Source: Prepared by the authors.

### 2.1. Normative approach and international guidelines.

In order to indicate those gaps and areas of opportunity that have been covered in the development of this work, a detailed analysis is carried out on the national regulations and seismic guidelines published in Spain. In this respect, the first Spanish normative text that refers to the seismic issue is "Chapter 7. Seismic Actions, of the MV-101 Standard on Actions in Construction" [19], published in 1962 with the objective of considering this type of event in the context of constructive design. Since this initial contribution, the influence of seismic effects has been taken into account in the "Instructions for the project, construction, and exploitation of large dams of the Ministry of Public Works" (IGP-1967) [20], and in the first state regulation of specific character published in 1968 under the title "Seismic-resistant Standard PGS-1/Part A". The aforementioned document never reached completion, and in 1974 it was replaced by the Seismic-resistant Standard PDS-1 [21]. In that same year the Permanent Commission of Seismic-resistant Standards was founded for the purpose of revising the seismic standard every five years. However, no subsequent normative update was made until twenty years later, with the publication of the "Seismic-resistant Construction Standard: General Part and Construction" (NCSE-1994) [22]. This document has been updated with the NCSE-2002 [23] for the general field of construction and with the "Seismic-resistant Construction Standard: Bridges" (NCSP-2007) [24], which is principally oriented towards the field of civil engineering. Both documents remain in force across Spain today, thereby illustrating that the five-year regulatory review period initially proposed is not currently being met.

The improvements provided in these updates have been found to provide criteria and specifications aimed at decisively influencing the quality of the residential buildings that have been built under the new regulations [25,26]. However, taking into account the normative panorama as indicated, a set of deficiencies can be detected, related to the actions in restoration work and to the evaluation of damage in catastrophic situations, that present a wide margin for documentary improvement. At the normative level, in Europe, the different Eurocodes and in the case study of Eurocode 8: Project of seismic-resistant structures [27], and more specifically, the various National Annexes particular to each of the countries, provide a series of common methods for the calculation of the mechanical strength of the elements that play a structural role in construction work.

In order to propose procedures that suppose an advance in the degree of detail of the norms and codes currently published in Spain, an approximation has been made to the panorama of seismic-resistance guidelines and protocols of post-catastrophe action that are published at an international level. Special attention has been paid to those countries and regions that have a greater documentary production in this subject. Most of these documents offer a series of general recommendations related to prompt actions. These recommendations are aimed at expediting the decision-making of the various institutional managers. In this respect, work by the Federal Emergency Management Agency (FEMA) in the United States [28,29] is of special interest, as is that by the New Zealand Society for Earthquake Engineering (NZSEE) [30,31], whose influence transcends publications in other countries with major seismic events, such as those in Japan [32]. The publication of guidelines in South America and Central America is also very common, with a high level of detail offered by the seismic codes in countries such as Chile, Colombia, and Mexico [33,34]. A large part of these documents is inspired by the requirements of the ACI-318, [35] as published by the "American Concrete Institute," the 2019 revision of which is about to be published. Its latest publication was in 2015 and included a version in Spanish and Chinese. In Europe, the development and importance acquired by these types of guidelines is of note [36], in countries such as Portugal, Italy, Greece, and in Turkey in the regions of Mediterranean influence.

The criteria and considerations collected in the study of the aforementioned documents highlight the importance that should be awarded to preventive studies that achieve the best possible development of "post-catastrophe" actions. Furthermore, their content has proven to be especially useful for the development of the short-term action protocol, primarily in the design and configuration of those parameters that form part of the readily prepared inspection records, as indicated in Section 3.1 of this document.

### *2.2. Main methods of evaluation.*

Based on the set of standards and guidelines consulted in the document analysis process illustrated in the preceding section, the main evaluation methods taken into account in the development of this work are those related to the configuration of parameters destined for the diagnosis of the state of conservation of a property following a seismic phenomenon. These methods are considered without undermining the importance and validity of those indicators related to the current level of risk that buildings endure in the face of future earthquakes. The main methods of analysis considered in the development of the project are specified below (Figure 2):

- Vulnerability indices (pre-catastrophe): Among the main indicators used in the risk-prevention study, that of the definition of the vulnerability index (Iv) stands out [10,11,37–39]. In general terms, the index is evaluated by weighting a series of quantitative and qualitative parameters that describe the current state of a building and its structural system.
  Its collection is based on the indications established by the GNDT II level [40], whose usefulness is largely associated with evaluation strategies prior to the occurrence of catastrophic phenomena, in order to prevent and minimize seismic damage. This method is based on the Risk-EU methodology [41]. This procedure quantitatively develops the vulnerability assessment proposal in accordance with the structural typology included in the European Macroseismic Scale [42]. In contrast, the first method of evaluation enables greater precision in the prediction of possible damage, by establishing a classification of the buildings and zones in accordance with the particular or general levels of vulnerability obtained.
- Diagnoses of immediate action (post-catastrophe): The principal methods and guidelines consulted opt for the use of simple and direct diagnoses that enable a clear determination of what the immediate action should be after a seismic event. This decision is associated with the extent of the seismic effect on the building, which can be determined through its general state of conservation, and through the state presented by its specific structural and constructive elements.
  The most usual casuistry proposes the establishment of three degrees of action: "apparently safe use", "restricted use", and "dangerous use". Through this determination, a first filter is achieved related to the functionality of the buildings after the catastrophe.
- Safety coefficients calculated from real values (pre- and post-catastrophe): Other studies focus on numerical analyses that assess the safety factor of the buildings after an earthquake. These procedures are also known as direct techniques [11] and, given the high degree of knowledge

required of the property to be evaluated, they tend to be used for the diagnosis of specific buildings, especially those classified as historical heritage [42,43], buildings with specific typologies with a high degree of typological and constructive homogeneity [44], and those that house general services whose operation is essential in case of catastrophe, such as hospitals [45–48].

This type of analysis usually requires a more detailed knowledge of the particular properties of the building, which are not always available directly, and often involve a major effort in prior characterization thereof. In turn, the determination of the safety coefficients is conditioned by the regulations in force at each geographical location.

However, the application of this type of method provides not only a complete and highly detailed view of the degree of particular resilience that each analysed building can present, but also the margin of safety that it may attain. In this respect, its contributions for the study of vernacular typologies in Portugal [44] and for the development of evaluations carried out in Italy [49] deserve mention.

• Classifications of structural strength assessment (pre- and post-catastrophe): This methodological approach, derived from the results obtained in the evaluation discussed above, constitutes an additional step that includes the process of calculating safety factors in specific buildings. In this respect, it is interesting to use classifications that refer to the level of structural safety (or quality) of a property against possible seismic phenomena, through the use of codes that allow buildings to be labelled in a similar way to the system employed for the energy rating of buildings. Similar classification procedures are currently used to estimate the degree of conservation of buildings in historical centres, thereby establishing priority for their intervention [50].

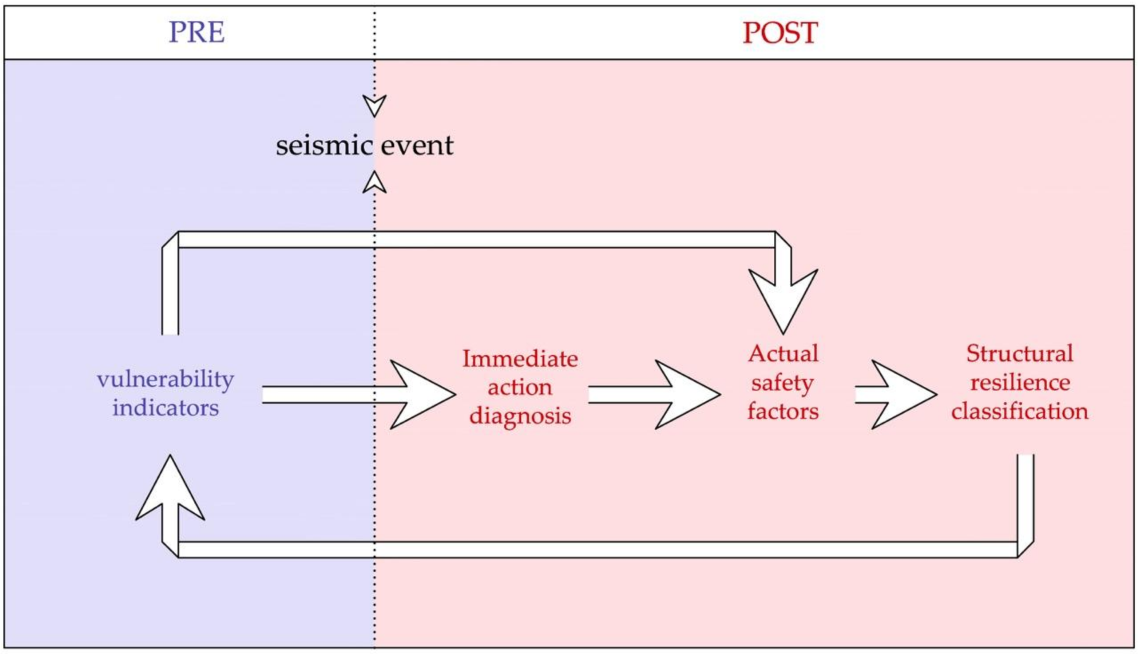


**Figure 2.** Diagram of the main analytical methods used in the research. Source: Prepared by the authors.

In order to carry out the evaluation of a building after an earthquake, it is essential, as a starting point, to have previous information about its safety conditions. The different procedures described above, allow a global analysis of the building, developing a structural characterization with a multiple approach. On the one hand, the risk-UE methodology provides the seismic vulnerability information in an easy and direct way, according to its constructive, morphological and typological characteristics. This information must be improved highlighting those points of the structure that a priori present greater vulnerability, that should be the object of special attention after the earthquake. This method, based on real values (dimensions of beams, material properties or reinforcements), provides an objective factor to assess safety: the higher the safety factor, the lower the risk of damage to the element analysed during an earthquake. Additionally, the procedures for immediate diagnoses (post-catastrophe) and classifications of structural strength assessment (pre- and post-catastrophe) have provided information on agile and effective inspection procedures, in order to estimate the structural response of a building. Thus, methodology procedures and a general and specific look over the building are combined to assess the survey and the evaluation after the earthquake. Through this approach, it can be observed how the application of these methods must be carried out through an iterative process that acquires validity in the episodes both before and after a seismic catastrophe. Each episode provides information of interest to achieve the various objectives, included in a common framework whose purpose is the optimization of resources and of management measures when faced with this type of catastrophe.

The vulnerability approach explained above, along with the local soil properties has been applied to the Andalusian region through a micro-scale analysis. The different methodologies provide indicators that can be plotted through micro-zoning studies, useful and necessary for a better control of the actual situation on the architectural scale. For this purpose, the use of geographic information systems (GIS) can be considered especially valid [51]. These systems, as collaborative instruments towards the management of this information through the open use of data, facilitate not only delocalised work between the technicians and professionals involved, but also the opening of communication channels that contribute towards the diffusion of the information generated.

### *2.3. Context conditions.*

The effect of the amplification of seismic waves in terms of the type of terrain establishes the local seismic hazard; this is known in seismic engineering as the site effect. Although several authors have conducted research to determine the amplification factors caused by this effect [52], in order to analyse the influence of seismic and geotechnical conditions of the terrain in constructions located in Andalusia, the main values and criteria specified in the NSCE-02 have been used; these regulations are currently in force at national level. This document requires the detailed characterization of the soil to a depth of 30 metres for the calculation of the seismic coefficient (C). This information, in spite of its obligatory nature, is seldom collected in the realization of geotechnical tests in building work. Indeed, several studies carried out in Lorca after the 2011 earthquake [53] have shown the importance of the study of the site at a geological level for the determination of the level of risk in the event of an earthquake, whereby a major part of the damage is derived from the lax consideration of its importance.

In order to define the geotechnical conditions of the Andalusian subsoil, additional material has been retrieved from the geological and geotechnical maps published at national level by institutions such as the Spanish Geo-Mining Institute (IGME). In this sense, regional studies related to the preparation of a geotechnical map of Andalusia have also been employed using GIS technology (Figure 3). A series of 1:400,000 scale maps have been produced by the project team, providing general information. On the one hand, thirty-eight basic soil units have been established for Andalusia, and on the other, the special conditions associated with karstic and expansive soils and landslides have been identified. All this information has been mapped in detail in a further set of cartographies that, using the 1:50,000 scale, provide in-depth information on the geotechnical characteristics of each Andalusian province.

Finally, this territorial approach has been accomplished with the help of institutional publications that address the study of risks in Andalusia [54]. Through these guidelines it is possible to corroborate the existence of zones that present a special seismic risk and that are geographically associated with the Baetic mountain system.

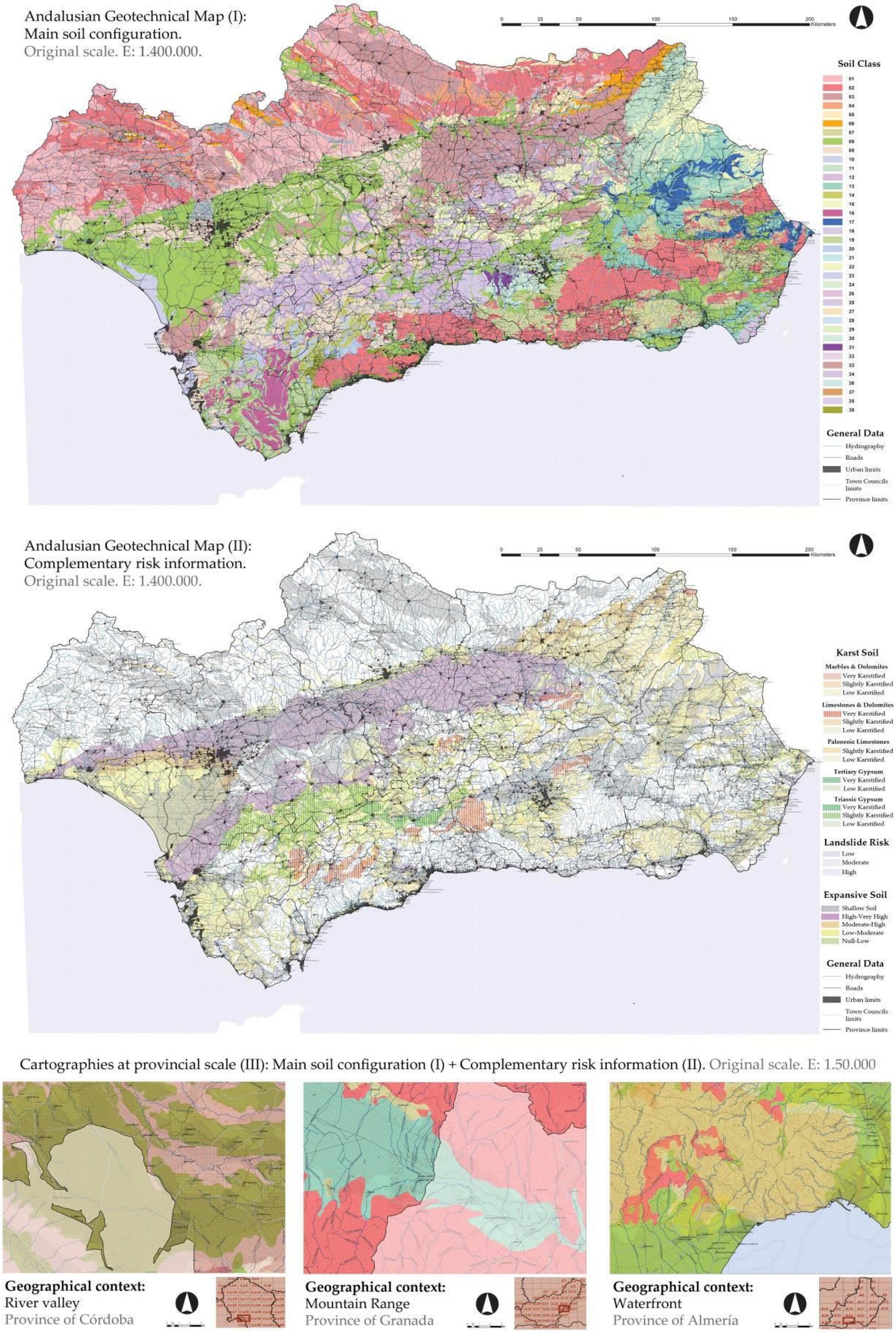


**Figure 3.** Geotechnical Map of Andalusia. General cartography and examples of detailed maps. Source: Prepared by the authors.

The analysis of this documentation has brought to light the existence of large documentary and informational gaps in terms of data for the calculation of seismic conditions at urban and architectural level. Although local studies have been carried out in provincial capitals such as Malaga [55], the micro-zoning work in the Andalusian territory cannot be considered to be general; there is therefore a deficit in the quantity and quality of this information.

Therefore, complementary to the assessment of the seismic vulnerability of residential buildings, and within the framework of the present investigation, specific maps of seismic micro-zoning have been drawn, based on the collected data, that take into account the evaluation of possible liquefaction phenomena in spaces representative of historical centres, as is the case of Seville [56].

### *2.4. General characteristics of Andalusian residential buildings.*

In relation to the specific topic of this work, a general study of the typological and constructive conditions of the housing in Andalusia has been made. The main analyses have been developed according to the structural and constructive systems used in different periods, complied from several Spanish regulations. In this respect, it is necessary to highlight the prevalence of the use, since the 20th century, of structural and constructive systems largely based on the production of bricks, in periods prior to the establishment of the first seismic regulations. Steel and especially reinforced concrete then became the most common structural typologies, compared to other materials such as rammed earth and wood. It is precisely through the most common architectural applications of these systems that a graphic catalogue has been constructed which enables the determination of the main damage that can be experienced by elements built following an event of seismic origin.

Moreover, it should be borne in mind that the large volume of residential stock was built before the second half of the 20th century. All those buildings that have yet to undergo a comprehensive review lack the protection of some type of regulation, code, or set of guidelines that pay specific attention to their possible structural and constructive behaviour in the event of an earthquake. Hence, it can be considered that this group of buildings is characterized by a recognizable heterogeneity and should be studied with a special degree of attention in future research related to the topic addressed herein.

### *2.5. Representativeness of the case studies.*

In order to analyse the characterization tasks in greater depth, the seismic-resistant conditions of a representative selection of case studies have been evaluated in detail, through the preparation of reports of seismic vulnerability relative to specific buildings. The properties have been selected based on their locations and are associated with geographical situations that may constitute a significant sample of the behaviour of certain residential typologies. Thus, from among the case studies analysed, residential buildings located in each of the eight provinces of the Andalusian region have been included, with priority granted to the study of collective housing blocks, especially those related to the public offer and built on the basis of revisable regulations. Furthermore, it should be borne in mind that preliminary information has been provided by the Agency for Housing and Restoration of Andalusia (AVRA), thereby contributing to the creation of the reports set forth in this subsection.

The case study reports have been written according to a general structure that enables a common working guide to be established for the inspection and seismic restoration of buildings. In this way, the analysed aspects in the different technical documents include the main issues that have subsequently been developed in the design of the short- and long-term protocols. As a result of this work, this methodology has been applied to different particular conditions that allow its general validity to be verified. Below, Table 1 provides a detailed description of the structure of the technical reports.

**Table 1.** General organization of the case study reports. Source: Prepared by the authors.

| Chapter | Main contents of each chapter |
|---|---|
| (1) Introduction | background; previous documentation; location; site-data; chronology; general risks conditions |
| (2) Seismic Vulnerability Factors | seismic regulations; seismic information; soils data; geometry of the built-up complex |
| (3) Constructive Description | foundation; structure; enclosures and partitions; roofs |
| (4) Building Survey | damage survey (cracks, material loosening); non-destructive tests (ground-penetrating radar, accelerometers, deformation leveling) |
| (5) Intervention Proposals | reinforcements; underpinning; bracings |

Consequently, the drafted documents provide a constructive and structural diagnosis of the case studies analysed, through the application of the main evaluation methods laid out in Section 2.2. In this way, the calculation of the real safety coefficients of the selected buildings has been carried out (Figure 4), by using finite element models (FEM) with the software SAP2000. The evaluation of the sections of their main structural elements has also been drawn by using the computer application of the Concrete Catalogue EHE 2008.

The results obtained using this software have allowed to establish patterns of structural behaviour for the typology studied. Thus, those specific points of the structure with greater vulnerability have been revealed. The use of linear static analysis has been considered suitable since the proposed methodology does not intend to be an exhaustive structural verification. More complex procedures such as nonlinear static analysis, linear dynamics analysis, nonlinear dynamic analysis are time consuming and their level of precision is not necessary in order to develop a preliminary assessment about the safety of a building after an earthquake. Additionally, when the situation has required it, non-destructive tests have been carried out to obtain additional information to characterize the structural properties of the buildings through the use of ground-penetrating radar, environmental measurements with accelerometers, or vertical deformation levelling [57].

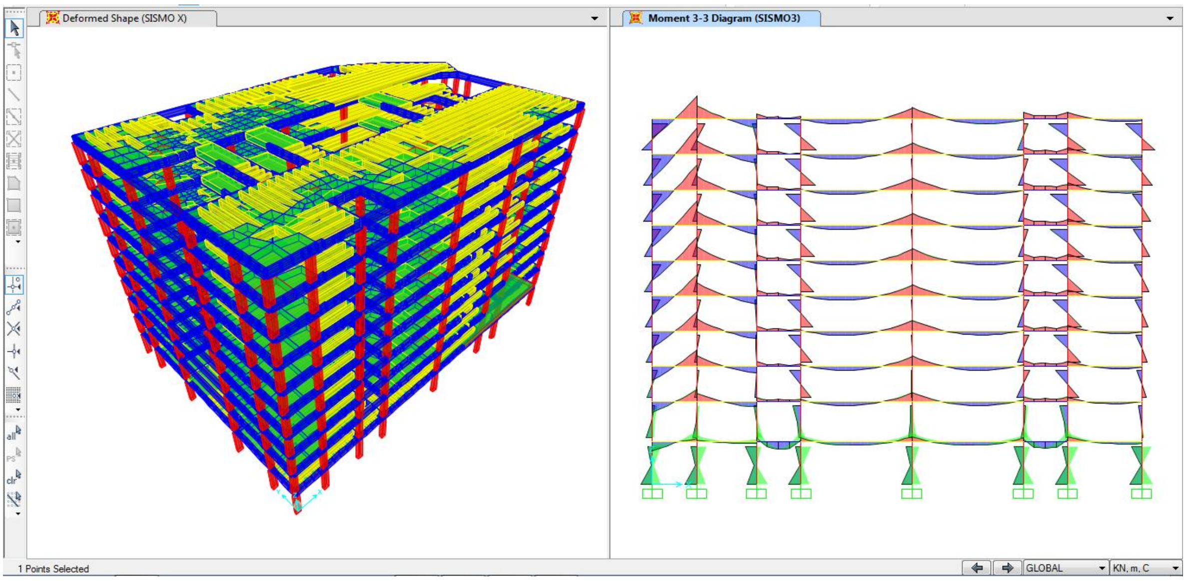


**Figure 4.** Digital model for the calculation by finite elements of officially protected housing built in 2003, located in C/ América 2, Cádiz (Spain). Source: Prepared by the authors.

Through this work, reference values have been obtained, suitable for similar cases. In turn, a structure for detailed analysis is provided that can be perfectly applicable for the seismic evaluation of numerous residential properties of similar characteristics.

## 3. "Post-catastrophe" seismic evaluation protocol for residential buildings in Andalusia

The structure of the information is organized into two main categories (Figure 5), which enable the consideration of the inspection activities and damage classification criteria that must be taken into account (short-term protocol). It also enables the illustration of the calculation procedures and constructive solutions that must be applied for the development of subsequent seismic restoration projects (long-term protocol).

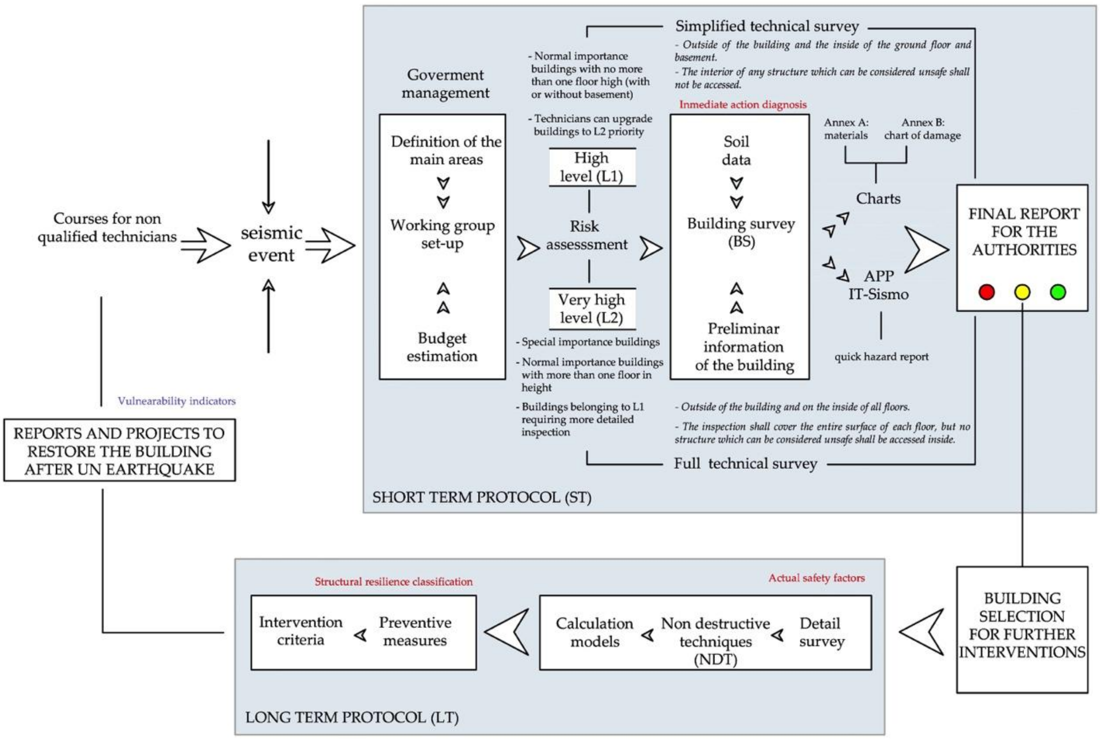


**Figure 5.** Process of evaluation and relation with short- and long-term protocols. Source: Prepared by the authors.

In this way, it is observed how all the preventive studies that have been developed throughout the project are materialized in a set of procedures and instruments aimed at the implementation of "post-catastrophe" actions.

At a general level, the use of the application for data collection in the analysis of the state of each of the buildings following a seismic event, would allow the management of all the reports in real time. Thus, the information related to the evaluated buildings would be included in a common platform that, based on GIS procedures, would allow the creation of urban maps in which to visualize the areas with the highest incidence of damage. This would facilitate the organization of the actions of the emergency teams following the earthquake, especially regarding short-term protocol.

### *3.1. Short-term action protocol: prompt post-earthquake assessment guidelines.*

The Protocol of short-term action is intended for the immediate inspection of residential buildings. This procedure includes a prompt action plan where the first guidelines for control, inspection, analysis, and evaluation of the state of the buildings affected by a major category earthquake are established. This document allows the stability of the inspected homes to be analysed and their degree of functional hazard to be determined depending on the damage detected. Once a short period of time has elapsed since the action of an earthquake, guidelines are employed to evaluate the state of material conservation of the built-up area and that of its structural and constructive elements. In order to ascertain the degree of safety of buildings following the disaster, a set of inspection checklists have been prepared based on the prescriptions provided by the main international guidelines [28,30,36].

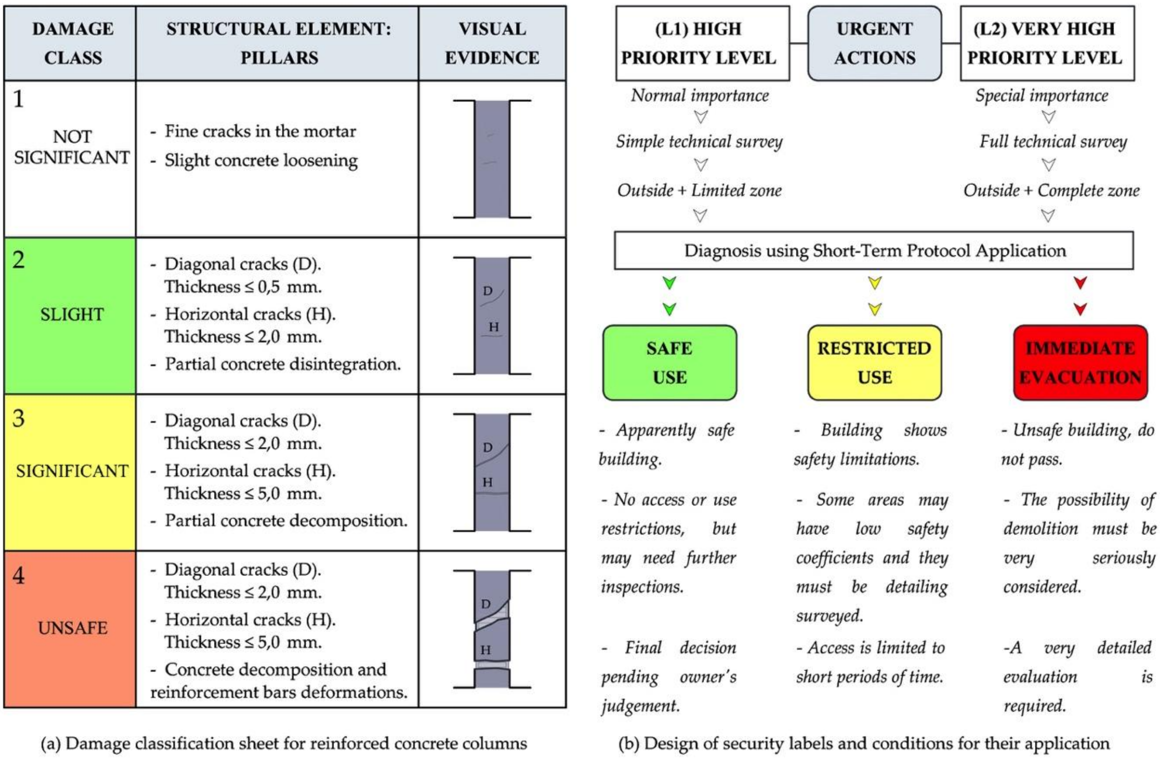


**Figure 6.** Damage classification sheets and measures to be taken depending on the inspection results. Source: Prepared by the authors.

Applying basic recommendations, the designed charts aid the classification of the damages in the building and enable the determination of its safety after the earthquake (Figure 6). These resources are designed to be used in quick assessments of damaged buildings, giving information about their degree of deterioration and avoiding more human lives lost. Therefore, the terms "Simplified technical survey" and "Full technical survey" are related to the resources used and the information provided in each type of inspection. This type of inspection is related to the "High" (L1) and "Very High" (L2) priority levels, which are established depending on the characteristics of the buildings checked and the need to repeat certain inspections, according to the obtained results. Through the consideration of the points included in this protocol, at a general level, the most sensitive points collected should be analysed in immediate inspections. These points include the following: Instability of the building due to the soil (settling, soil liquefaction, landslides, etc.); collision between buildings due to insufficient joints for seismic movement; breakage of short pillars in semi-basements; breakage of pillars on the ground floor due to changes in stiffness; loose façade elements and structural joints failure.

Once all the above points have been considered, the technician responsible for the inspection is guided by the information included in the document regarding the results of the diagnosis in relation to the actual safety level of the residential building inspected after the occurrence of the seismic event. In this respect, three general levels are provided [31]: Safe (green label: the building has minor damage, there is no access restriction); Restricted Use (yellow label: affected areas are detected, passage is prohibited except for extraordinary circumstances); Immediate Evacuation (red label: damage that can affect the stability of the building, passage is forbidden).This document is designed to guide the technicians responsible for carrying out technical inspections in their decisions as to which principal factors and parameters should be considered during said inspections: work teams, geometry and location of the building, constructive elements and technical requirements of the regulations in force. This set of guidelines is proposed as an instrument for professionals in the field of architecture and engineering, who, without being specialized in seismic events, can perform collaborative work, essential under this type of circumstance, with greater knowledge.

In order to facilitate the use of the contents of the protocol in the short term, the possibility of designing an interactive tool was proposed for the automatic completion of the inspection forms. Based on this objective, the IT-Sismo Andalucía APP was created, which can be considered as one of the most innovative contributions of the present research.

### 3.1.1. Application for IT-Sismo Andalucía mobile devices

As indicated above, the contents of the short-term protocol have been integrated into an application for mobile devices (cell phones and tablets) in the Spanish language. This application provides interactive tools for the development of the aforementioned diagnosis and the possibility of producing drawings and taking photographs that could be included in the final evaluation report. This document is generated automatically, following the completion of the fields of information that appear in the sequence offered by the digital tool.

Among the various options of functionality that have been considered, it was decided, in consensus with the technicians of the supervising institutions, that the application could work without an internet connection. In this way, the APP becomes operative through a simple process of prior download and subsequent installation on the inspecting technician's device. This is carried out in anticipation of the possible problems of connectivity and access to data that may occur in the event of a catastrophic situation. With this approach, it is intended to eliminate a possible dependence that could be experienced by the technicians in charge of the various inspections.

The first contact of the user with the application occurs via the presentation screen, which provides an introduction regarding the characteristics of the project, as well as a set of recommendations aimed at facilitating its use. To this end, the contents of the protocols explained above are provided, as well as a manual for the tool itself. Once the users have become familiarised with the aforementioned contents, they will be able to use the interactive protocol to good advantage (Figure 7).

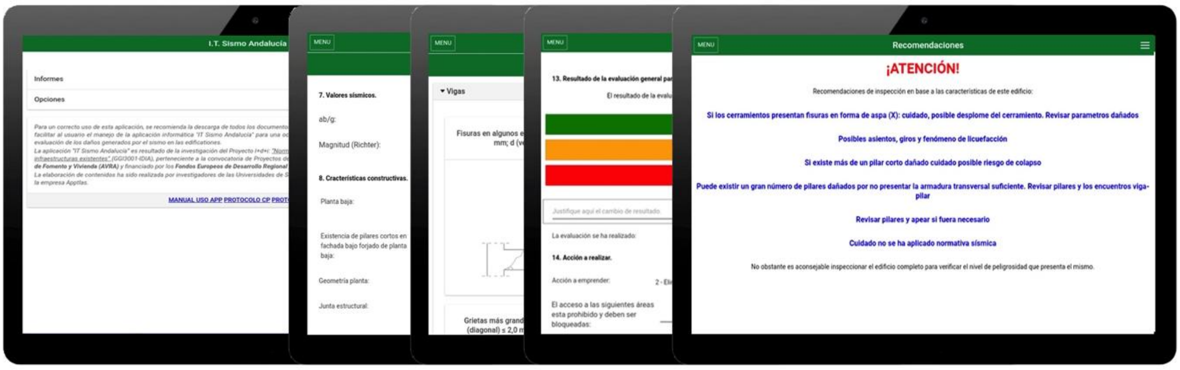


**Figure 7.** Several screenshots of the ICT tool developed for the assessment of existing buildings and infrastructures (IT-Sismo). Source: Prepared by the authors.

The tool enables the creation of diagnostic and evaluation reports, and also the editing, deletion, and downloading of all the preliminary versions that the user deems appropriate. Once the results achieved are verified as being those expected by the technicians, the generated contents can be validated through their signature. This option implies a blocking of the generated report, which remains stored in the user's personal file, and can be sent to the competent institutions. All the reports are structured into three large blocks, which must be completed consecutively:

• General information: Initially, the technician completes the data in a first phase by providing general information related to the work team, the building, and the soil upon which its foundations lie. On the screen related to the work team, information relating to the type of inspection carried out can be included as can the contact details of all members who make up the inspection squad which must be coordinated by a technician responsible for verifying the final document. The section related to the property data requires the definition of its location, its chronology, its volumetric characteristics, its materiality, and the nature of its typology. Through the last screen, related to the soil-structure interaction, the tool automatically contributes the values related to the seismic coefficients of the soil (*ab*/*g* and K) from the site indicated, and allows the introduction of the values of the magnitude and intensity experienced during the earthquake. These parameters are used by the APP to classify the type of damage and are usually related to the occurrence of each kind of seismic event. Likewise, the definition of the main constructive and structural characteristics that influence the interaction with the soil is considered, as are the values of the fundamental period of the building that could be measured with sensors integrated in mobile devices.

• Inspection*:* The information provided in this first block allows the tool to supply a series of recommendations for the development of the second phase of the work, related to the detailed inspection of the architectural elements of the building. From this phase, a set of fields are activated that relate to the different materials introduced in the previous phase. In this way, independent interactive forms are established that work as guidelines for the quantification of the percentages of damage experienced with respect to all the constructive and structural elements of the building that have been fabricated in concrete, steel, stonework, and/or wood. Concerning these material categories, a second differentiation is established between resistant elements, auxiliary elements, foundation failures, and general movements. In addition, and due to their importance in the evaluation process, the resistant elements are again categorized through the following concepts: beams, pillars, walls, joints, floor slabs, and stairs. In those categories of most common damage, the tool provides graphic diagrams and images that allow the user to visually identify the type of damage referenced in the field to be filled. Additionally, the application allows photographs to be taken and drawings to be made through the mobile device itself, which can be stored and included as documentation attached to the report generated.

• Damage Assessment*:* In order to quantify the damages to the building and its risks, the different elements are classified in groups based on their typology, from A to D, and each of them is given a label depending on the severity of the damage (classes from 1 to 4). Combining the severity of damages and its spread percentage, the building will be labelled in a different group as the following chart shows (Table 2).

**Table 2. S**tandards for the assessment of particular elements. Source: Prepared by the authors.

| Group | Description | Damage class | Damage spread (%) | Group label |
|---|---|---|---|---|
| A.1 | Main structural elements: beams, pillars, joints, load-bearing walls, etc. | 1-2 | 25-50 | Green |
| | | 1-2 | 75-100 | Yellow |
| | | 3 | 25-50 | |
| | | 3 | 75-100 | Red |
| | | 4 | 25-100 | |
| A.2 | Horizontal or inclined structural elements: slabs, floors, stairs, roofs, etc. | 1-2 | 25-50 | Green |
| | | 1-2 | 75-100 | Yellow |
| | | 3 | 25-50 | |
| | | 3 | 75-100 | Red |
| | | 4 | 25- 100 | |
| B.1 | Non-resistant elements: masonry walls, fillings, partition walls, enclosures, etc. | 1-2 | 25-100 | Green |
| | | 3 | 25-50 | |
| | | 3 | 75-100 | Yellow |

| | | | | |
|---|---|---|---|---|
| | | 4 | 25-50 | |
| | | 4 | 75-100 | Red |
| B.2 | Auxiliary elements: parapets, chimneys, roofing elements, tiles, coverings, glassware, lighting, antennas, etc. | 1-2 | 25-50 | Green |
| | | 1-2 | 75-100 | Yellow |
| | | 3 | 25-50 | |
| | | 3 | 75-100 | Red |
| | | 4 | 25- 100 | |
| C | Building verticality | 1-2 | Not applicable | Green |
| | | 3 | Not applicable | Yellow |
| | | 4 | Not applicable | Red |
| D | Soil and foundations | 1 | Not applicable | Green |
| | | 2 | Not applicable | Yellow |
| | | 3-4 | Not applicable | Red |

By means of empirical rules and qualitative methods that have been checked and validated by experts, a specific label is assigned to the building depending on the combination of the amount of damage and its spread. The following chart determines the overall assessment of the affected building according to the degree of damage established in each group of elements (Table 3).

**Table 3.** General building assessment and label criteria. Source: Prepared by the authors.

| Groups | Group label | Proposed group combination | Building label |
|---|---|---|---|
| A.1 or A.2 or B.1 | Red | 1 | Immediate evacuation |
| A.1 or A.2 or B.1 | Yellow | 2 | Restricted use |
| and | and | | |
| B.2 | Green | | |
| A.1 or A.2 or B.1 | Yellow | 3 | Immediate evacuation |
| and | and | | |
| B.2 | Red | | |
| A.1 and A.2 and B.1 and B.2 | Green | 4 | Restricted use |
| and | and | | |
| C or D | Yellow | | |
| A.1 and A.2 and B.1 and B.2 | Green | 5 | Immediate evacuation |
| and | and | | |
| C or D | Red | | |
| A.1 and A.2 and B.1 and B.2 | Yellow | 6 | Immediate evacuation |
| and | and | | |
| C or D | Yellow or Red | | |
| A.1 and A.2 and B.1 | Green | 7 | Safe use |
| and | and | | |

| | | | |
|---|---|---|---|
| B.2 | Yellow or Red | | |
| and | and | | |
| C and D | Green | | |
| A.1 and A.2 and B.1 | Green | | |
| and | | | |
| B.2 | Yellow or Red | 8 | Restricted use |
| and | | | |
| C and D | Yellow or Red | | |
| A.1 and A.2 and B.1 and B.2 and C and D | Green | 9 | Safe use |

The aforementioned procedure has been implemented in the IT-Sismo App, so that once each indicator is typed in, the software generates the label. The evaluation of the collected data through the app allows the architect or engineer to correctly label the building. In any case, the technician will be able to edit the results obtained and include comments that help understand the document, prior to its final validation.

### *3.2. Long-term Intervention Protocol: Guide to Seismic restoration.*

This document is proposed as a guide for the creation of technical reports that require prolonged development over time. This document presents the work and actions that technicians must take into account in order to carry out a more detailed analysis, regarding the restoration and/or demolition of the properties that require this type of revision. In this way, the scope and objectives of this document are related to the contribution of criteria for the evaluation of seismic behaviour in existing buildings, the description of possible corrective measures to be used in a restoration process, and the orientation in the development of tasks related to the analysis of the structural types, the recalculation of the affected elements, and the sizing proposals of the new parts to be incorporated in reinforcement and/or refitting operations.

The long-term intervention protocol establishes the systems that check and verify existing structures. These systems are necessary for the analysis of the behaviour of buildings if, where applicable, they have to face an earthquake of high intensity. This document is aimed towards orienting the calculation of the current structural safety coefficient of the constructions before dynamic action, towards evaluating their degree of conservation, and towards proposing new safety indices, especially of either those buildings whose typological and constructive characteristics are representative of most of the domain of the Andalusian region, or of constructions of a patrimonial nature. In this case, the conditions of buildings of a historical nature are tackled.

Here, specific calculation and modelling criteria are taken into account for the structural evaluation of the housing, as are structural and constructive solutions for the reinforcement and repair of damaged elements. One example includes the establishment of new safety coefficients and highly specific test systems, such as those based on the determination of the natural frequency of vibration.

The protocol will be accompanied by a series of technical recommendations, and by possible actions of reparation, restoration, and reinforcement, aimed at improving the capacity of the buildings to be resistant to future earthquakes, whereby as little as possible of the previous configuration is altered, and increasing its safety in the event of an earthquake [32].

## 4. Discussion

With the arrival of the 21st century, a gradual awareness has arisen regarding historical seismic risk, especially in regions where the incidence of earthquakes of high magnitude and intensity is rare. This is the case of Andalusia, in the south of Spain, where historical records reveal the occurrence of earthquakes with an intensity of IX or higher; such as the earthquakes of 1504, 1755, and 1884 [58,59]. Due to its long recurrence interval, there has traditionally been a lack of awareness of this risk. This level of awareness has increased in recent years, whereby certain municipalities have developed action plans in case disaster strikes, although this preparation has yet to be generalized. These plans not only should include a set of action protocols, but they must also incorporate specific procedures regarding the inspection of damaged buildings and the way to proceed in the management of the information generated.

After a seismic event of an intensity greater than VI, it is necessary to carry out an inspection of the properties and affected areas in order to detect their degree of safety. Given the workload, it is imperative to have a specific tool that enables a quicker assessment and also the operational administration of the amount of information generated, so the most effective decisions for the management of the possible catastrophe can be adopted in real time. In this sense, those strategies designed for the development of such a complex documentary set, established as a "post-catastrophe" protocol on a regional scale, have been combined in a proposal of a methodological nature. This is achieved through the development of an electronic application installed on a mobile device, that serves as a guide for the inspection, and which also enables the establishment of a regulated procedure for data collection.

This tool can be used by the technicians in charge of carrying out the inspections and allows all the information to be downloaded onto a common platform which aids the management and decision-making process by the authorities.

The specific information included in the short-term protocol comes from the analysis of the general constructive conditions of residential buildings in Andalusia, and from examples of damage taken from the studies collected in this work. In order to expedite an inspection process that must be carried out urgently, an application for mobile devices has been developed for the automation of diagnostics. Fortunately, no seismic event has yet led this work to be put directly into practice. However, testing has been carried out through a verification of the coherence and logical value of the results. To this end, eight case studies, namely eight residential buildings developed by the public administration, have been introduced in the App and evaluated. These results were compared with a prior manual evaluation of researchers and technicians for the same buildings and by means of improvement cycles, the procedures were adapted until the outcome of the App matched the manual evaluation. The proposed methodology has been tested in numerous case studies proving its effectiveness during a post-earthquake evaluation. To do this, based on the selected group of residential buildings, multiple damage scenarios have been designed and applied to buildings with different structural and constructive characteristics. All the results obtained have been contrasted by the authors of this work and researchers of the project to verify the suitability and logic of the results obtained. This has allowed to optimize the use of the APP.

Furthermore, the diagnosis reports applied to the selected case studies have enabled the calculation conditions to be verified for the creation of the protocol in the long term; a set of guidelines has been designed systematizing those aspects that a seismic restoration proposal for residential buildings in Andalusia should include.

Additionally, the tool has been shared in teaching sessions with students and non-specialist technicians, demonstrating the usability and viability of the digital version of the protocol through the IT Sismo APP. This illustrates the usefulness of ICT tools in the evaluation of technical aspects that require a high degree of specialization.

## 5. Conclusions

The proposed methodology has been developed to assess residential buildings considering a two-step analysis. The first step of the evaluation concerns the preliminary work that has been proved to be easy to implement for any residential building, and most importantly, it can be used by non-experts with few resources, so that in case of seismic event it is a more efficient way to cover the evaluation of a greater number of affected cases.

It should be pointed out that the creation of reports in digital format, as an outcome of the IT-Sismo APP, facilitates the inspection and speeds up the institutional management of the post-catastrophe files that are generated during the process. This procedure also allows the management of the information obtained, thereby increasing the level of efficiency by reducing the time allocated to data collection and the preparation of a comprehensive diagnosis.

As this innovative proposal is the first of this kind in Andalusia, it should be considered as an initial approach; hence the methodology can be improved in certain ways. For example, other structural types or construction buildings materials need to be evaluated, since within the building stock in Andalusia we can find many of them dated before the 20th century, and therefore a new perspective on the traditional constructive systems should be considered. As this proposal is a result of a public funded project, the authors suggest that this tool should be implemented within the workflow of the administrations in charge of the maintenance of the building stock, either by means of the off-line tool or a future on-line one.

Finally, this proposal should also serve as a reminder that society must remain alert (and prepared) for the occurrence of phenomena, that in Spain (and more specifically, in Andalusia) are rare, but could also be catastrophic.

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