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Andy Combey, Agnès Tricoche, Laurence Audin, David Gandreau, Carlos Benavente Escóbar, et al.. Monumental Inca remains and past seismic disasters: A relational database to support archaeoseismological investigations and cultural heritage preservation in the Andes.. *Journal of South American Earth Sciences*, 2021, 111, pp.103447. 10.1016/j.jsames.2021.103447 . hal-03342482

HAL Id: hal-03342482

<https://hal.science/hal-03342482>

Submitted on 13 Sep 2021

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This is a version close to the Accepted Manuscript, which has been through the *Journal of South American Earth Sciences* peer review process and has been accepted for publication (VSI:8th ISAG Special Issue). The published Journal Article (PJA) is available on the [ScienceDirect webpage](#). Please note that technical editing may introduce minor changes to the text and/or graphics. Feel free to contact any of the authors; we welcome feedback.

Monumental Inca remains and past seismic disasters: A relational database to support archaeoseismological investigations and cultural heritage preservation in the Andes.

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Keywords

Archaeoseismology, Database, Seismic Hazard, Cultural heritage, DRR, Cusco

Abstract

As recent dramatic and numerous examples demonstrate, earthquakes still constitute a significant threat to cultural heritage (Bam 2003, L'Aquila 2009, Haiti 2010, Nepal 2015). By damaging the historical legacy, telluric phenomena affect economic and touristic incomes and alter regional identities and collective psyche. In the Andes, as in other emerging regions across the globe, deficient seismic hazard assessments, constant lack of resources, and inadequate maintenance programs are additional challenges for cultural heritage management. As part of our archaeoseismological investigation in the Cusco area (Peru), we developed a relational database, which seeks to identify, record and inventory seismic damage in pre-Columbian architecture. This work presents the main characteristics of the structure and design of the RISC ("Risque sismique, Incas et Société à Cusco") database and its contribution in supporting the fieldwork organization and facilitating the data acquisition. The collected architectural evidence constitutes the first large archaeoseismological dataset in South America and will provide valuable complementary data in Peru to regional seismic hazard studies. We here aim to demonstrate that an ergonomic and user-friendly interface has a role to play in supervising and preserving the cultural heritage in active seismic areas. By converting *ad-hoc* surveys into routine inspections, RISC could become an effective low-tech monitoring system, providing

relevant support for disaster risk reduction plans in archaeological sites conservation. We stress the necessity of adopting cost-effective and easy-to-implement tools for cultural heritage monitoring in emerging countries through this case study. Our database may represent a relevant methodological background and template for further initiatives in both fields of archaeoseismology and cultural heritage protection.

1. Introduction

As a social, cultural and symbolic act, architecture and, more specifically, the built heritage is an integral part of the collective memories and traditions (Caimi, 2014; Garnier et al., 2013; Ortega et al., 2017). In 1972, during the General Conference of the UNESCO, State parties agreed on the necessity of “ensuring the identification, protection, conservation, presentation and transmission to future generations of the cultural and natural heritage” (UNESCO, 1972, Art.4). To do so, the international organization proposed several guidelines related to seismic hazard mitigation (UNESCO, 2007, p. 173): “reducing risk through ensuring maintenance,” “strengthening buildings,” “improving earthquake warning systems” as well as “developing comprehensive earthquake plans.” The creation and development of monitoring systems thus represent a prerequisite to follow those preparedness guidelines correctly.

Identifying earthquake evidence and damage in archaeological remains has long been seen as a re-active investigation. Archaeoseismologists intervened “after” a seismic event with the objective to improve the seismic catalog and thus better assess the regional seismic hazard. Hence, ancient human settlements and monuments have turned out to be valuable markers of past seismic activity, providing complementary information to the traditional geomorphological and paleoseismological studies and filling the gap between prehistorical and instrumental seismology (Karakhanyan et al., 2010; Noller, 2001; Silva et al., 2005; Similox-Tohon et al., 2006). The recent shift from qualitative to (semi)quantitative methods not only strengthens the archaeoseismological methodology and its scientific basis (Ambraseys, 2006; Galadini et al., 2006; Sintubin, 2013) but also provides a great opportunity to connect the research field to proactive strategies such as risk management and disaster risk reduction (DRR) programs in the context of cultural heritage protection (Jusseret, 2014; Sintubin, 2011). Indeed, the large-scale registration of Earthquake Archaeological Effects (EAE – Rodríguez-Pascua et al., 2011), the use of remote sensing tools (Lidar, photogrammetry – Forlin et al., 2018; Yerli et al., 2010) as well as the construction of seismic deformation simulation thanks to 3D models (Hinzen et al., 2013; Hinzen and Montabert, 2017; Pecchioli et al., 2018) constitute important steps towards monitoring strategies of archaeological remains. Addressing the impact of past earthquakes on cultural heritage has turned into an emerging priority, particularly in the Mediterranean area (Marchetti et al., 2017; Montabert et al., 2020; Remondino and Rizzi, 2010). However, in South America and across the High Andes, research is still at its early stage (Aguilar et al., 2015; Briceño et al., 2018; Noel et al., 2019). In Peru, considered as the most vulnerable country of the continent in terms of seismic hazard (Stillwell, 1992; World Bank, 2012), increasing the

risk preparedness and resilience of built heritage requires innovative and multipurpose approaches. To fill this gap in the Cusco region, we propose the implementation of a new database designed to characterize the level of damage of the cultural heritage facing earthquake threats (or even broader natural disastrous events).

2. Research aim

The Cusco area stands out for its rich pre-Columbian and colonial heritage. While the area and its monuments were severely affected by past ground shaking episodes, the current seismic hazard remains poorly assessed and its implications in terms of heritage vulnerability sometimes even overlooked (Carlotto et al., 2007; Noel et al., 2019). In the framework of the archaeoseismological project RISC (“Risque sismique, Incas et Société à Cusco”), we developed a user-friendly database, whose aim was to keep a record of potential seismic effects observed in Inca remains (ca.1300-1532 AD). Initially designed as an ephemeral data collection tool, the RISC database has turned into a permanent platform for data mining. Taking into account the main challenges that South America has to face in terms of cultural heritage preservation (Gamboa, 2016; ICCROM, 2004), we consider the use of large and organized datasets in archaeoseismological studies as a particular promising resource to improve the seismic vulnerability assessment and management of numerous touristic archaeological sites. Through this case study, we hope to offer a valuable database template, easy to use and adapt for future research.

3. Theory

3.1 Seismic risk in the Andes

Social vulnerability to earthquakes is a crucial challenge in the coming years, exacerbated by the constant and rapid urbanization processes (Jackson, 2006). The increasing exposure is probably even more acute in South America and especially all along the Andes. Actually, the mountain range that borders the western part of the continent concentrates an overwhelming majority of the current seismic strain and deformation rate (Costa et al., 2006; Dewey and Lamb, 1992). The Andean region is also marked by a high density of population compared to the rest of South America, hosting mega-cities like Santiago, Lima, Quito or Bogota. Recent seismic risk assessment evaluates that more than one-third of the total population of the continent “may experience strong ground shaking in a 50-yr period (2%

probability of exceedance in 50 yrs)” and 30 millions of people “reside in areas of high hazard where earthquakes are quite likely (50% in 50 yrs)” (Petersen et al., 2018). Anarchic urban sprawl, informal settlements and deficient building standards are aggravating factors that alter the capacity of Andean societies to cope with violent ground motion episodes.

Unfortunately, little is still known on the quaternary deformation and associated seismic activity (Costa et al., 2006). Suffering from huge discrepancies between inter-plate and intra-plate seismicity (England and Jackson, 2011), the current global seismic risk assessment remains heterogeneous and too poor in many regions distant from the active tectonic margins. Unlike the well-monitored subduction seismicity, scattered active crustal faults in continental interiors are not sufficiently mapped and characterized (motion type, return period, strain rates... - Petersen et al., 2018). Local and regional models for seismic hazard assessment, first attempt to set up a scientific basis for political decision-making, are still in their infancy (Das et al., 2020; Leyton et al., 2009) and few are the ones that consider shallow crustal seismicity (Aguilar et al., 2017; Asociación Colombiana de Ingeniería Sísmica, 2010; Beauval et al., 2018; Yepes Arostegui, 2015).

In such active tectonic areas, traditional approaches (e.g., instrumental seismology, tectonic geomorphology and paleoseismology) appear to be insufficient to assess properly the seismic hazard and risk. The lack of intelligible written sources before the Spanish Conquest (mid-sixteenth century) diminishes the potential of historical seismic studies substantially. Cross- and multi-disciplinary approaches are therefore needed to improve the regional seismic catalog and get an appropriate resolution to the moderate-low return period associated with crustal faulting (Blumetti et al., 2017; Liu and Stein, 2016). Archaeoseismology has demonstrated to be particularly well suited to address this issue and link accurate instrumental data from the last century with long-time sedimentological/limnological records (Caputo et al., 2006; Meghraoui and Atakan, 2014; Sintubin, 2013; Stiros, 1996). The built archaeological heritage of South America, whose history spans at least the two last millennia, represents a promising marker of past seismic activity. Results may complement scanty colonial accounts and improve the dating of poorly constrained seismic events evidenced in paleoseismological trenches.

As the result of centuries of building experiments, the cultural heritage reflects a long empirical learning process with regard to seismic hazard. However, given its complex history and our inability to manage it properly, this legacy constitutes one of the most vulnerable sectors with respect to earthquakes and thus requires special attention. Unfortunately, it remains too often a second-ranking priority for emerging economies.

3.2 Challenges of the conservation of the cultural heritage

While cultural heritage and particularly archaeological sites play a crucial part in the identity construction process of southern American countries (national symbol, self-esteem, touristic income), the lack of financial resources hampers ambitious conservation plans (ICCROM, 2004; Sevieri et al., 2020). Governments dedicate most of their funding legitimately to reduce poverty and support the productive economy and are thus not able to preserve adequately their Cultural assets (Heras et al., 2013; ICCROM, 2004). A lack of institutional memory in public institutions and authorities as well as issues in terms of formation of the persons in charge of the Conservation work are two supplementary factors that explain dysfunctions in the cultural heritage preservation policies (Jokilehto, 2015). Despite the recent effort to overcome those problems, a report requested by the World Heritage Committee in 2006 stated that “most world heritage properties, particularly in developing areas of the world, do not have established policies, plans and processes for managing risk associated with potential disasters” (World Heritage Committee, 2006, p. 1). However, cultural heritage buildings are even more at risk because of their great age as well as the several constructive phases and the inadequate human interventions that may have affected them (Despotaki et al., 2018; Díaz Fuentes et al., 2019; Ferrigni et al., 1993; The Getty Conservation Institute, 2015).

Regarding the seismic risk, one main interrogation is nonetheless raising: how do we protect the cultural heritage from a natural hazard that is intrinsically unpredictable and uncontrollable? In case of an earthquake, it is impossible to remove the causative factor of damage, but it is possible to mitigate it (Feilden, 1987). The main organizations and institutions involved in the conservation field advocate for preferring a pro-active (preventive) approach to a re-active (curative) one (Feilden and Jokilehto, 1998; Jokilehto, 2000; UNESCO, 2010; Van Balen, 2017). Considered as the best-cost-effective strategy, the preventive approach aims to maintain authenticity by reducing the building’s vulnerability and limiting the potential destruction. That results in expensive retrofitting works but also in more modest monitoring devices and condition assessment surveys to assess the seismic vulnerability of the buildings (UNESCO, 2010). Monitoring is based on the concept of time and change and supposes the existence of constantly updated documentation about the heritage of interest and the potential vulnerability factors (Gandreau and Delboy, 2012; Paolini et al., 2012; Van Balen, 2017). Archaeological and historical buildings need, therefore, to be considered in a long-term perspective (Stovel, 1998). Earthquakes experienced by the buildings in the past as well as their consequences, are particularly helpful in making the best diagnosis. Prerequisite to any conservation decision

(ICCROM, 2004), monitoring has to rely on a multi-sectoral and collaborative approach (UNISDR, 2015).

Databases appear to be well-suited to organize large sets of data and ensure standardized and harmonized methodologies. As it has been previously demonstrated, they are particularly helpful for supervising cultural heritage (Berg, 2007; Zerbini, 2018) and supporting systematic processes of damage assessment (UNESCO, 2010). How can the system be nevertheless more useful for safeguarding the heritage? An archaeoseismological database may provide relevant input data for future risk reduction.

4. Material and methods

4.1 Overview of the RISC project

Famous worldwide for its cultural heritage, including notably the Cusco city and the Machu Picchu archaeological site inscribed both on the World Heritage List (<https://whc.unesco.org/fr/list/>, last accessed July 25, 2021), the Cusco region (Peru) is less known for its recurrent and potentially destructive seismicity. As various Andean regions distant from the subduction trench and as explained in 3.1, the Cusco area suffers from a poor understanding of its crustal seismicity. The concise historical catalog (Silgado Ferro, 1978; Tavera et al., 2016) available, coupled with still scarce paleoseismological studies (Benavente Escobar et al., 2013; Cabrera and Sébrier, 1998; Palomino Tacuri, 2020; Rosell Guevara, 2018), does not allow to assess properly the return period of the numerous active faults of the region, which triggered damaging earthquakes in historical (1650, 1950, 1986) and pre-historical times (Combey et al., 2020). We decided thus to develop the RISC project, whose objective is to improve the seismic hazard assessment by implementing the first large archaeoseismological survey in South America. Due to their particular and massive megalithic architecture, monumental Inca settlements of the Cusco and Sacred Valley constitute well-suited “seismoscopes” (Sintubin, 2013) that may have recorded large ground motion events since the fourteenth century (Rodríguez-Pascua et al., 2019). The location of numerous Inca sites in seismically active areas during the instrumental period (since 1960) as well as their distribution near active normal faults, emphasize their archaeoseismological potential (Fig.1a). We surveyed 17 monumental archaeological sites of the region (Fig.1a) with the objective to identify and register EAE, i.e., architectural damage, direct consequences of seismic activity (Fig.2).

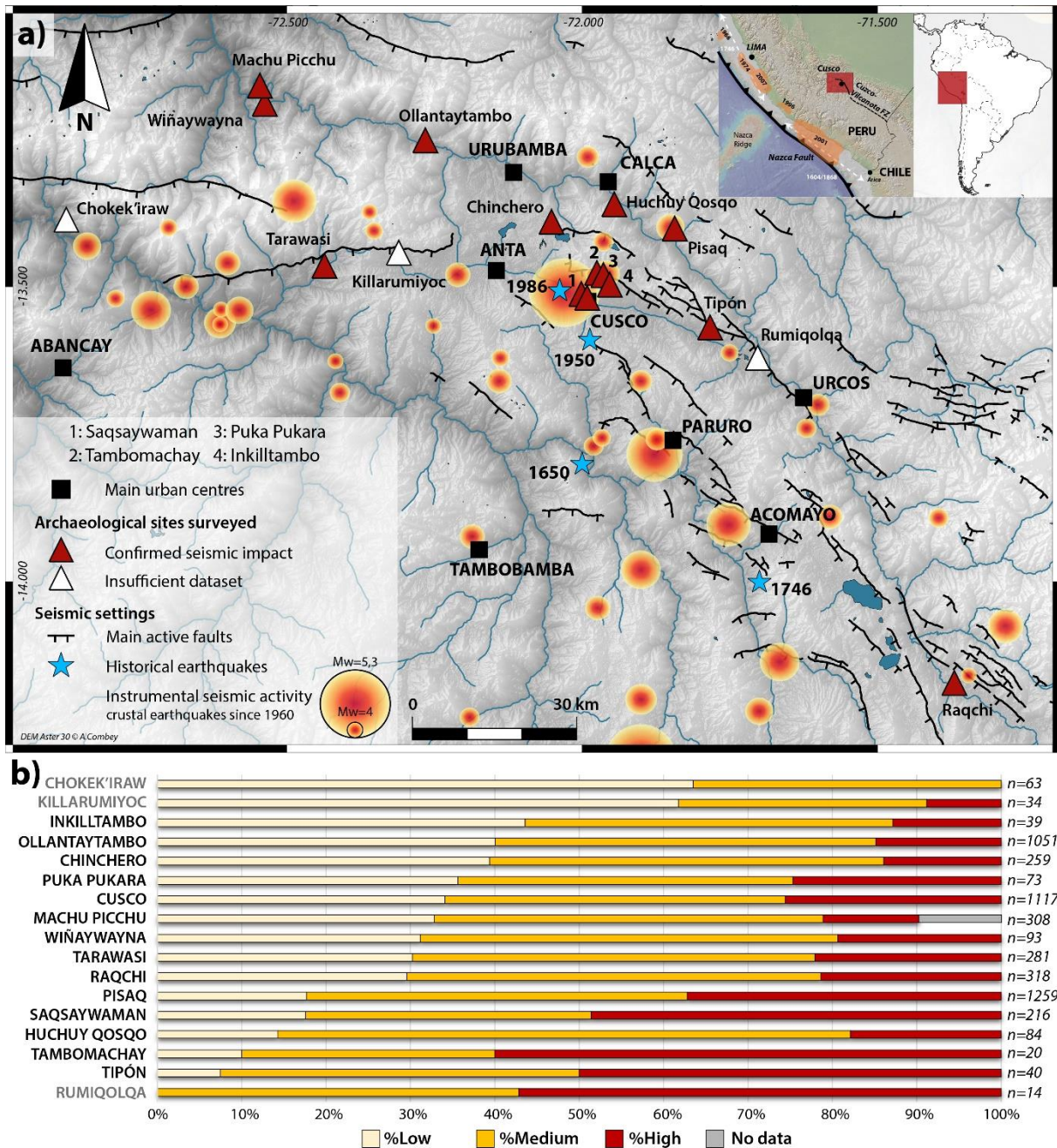


Fig.1. a) Cusco regional map displaying the main active seismic areas during the last 60 years (instrumental seismicity) and the location of the 17 archaeological sites surveyed during the RISC project. The size of the buffer zones depends on the estimated rupture length for each seismic event (see Supplementary 1). Information on historical earthquakes (blue stars) is based on Ericksen et al., 1954; Silgado Ferro, 1978; Tavera et al., 2016; b) Proportion of High, Medium, and Low levels of confidence of EAE records for each archaeological site. The chart displays the results of the previous database version, i.e., the level of confidence is only based on the assessment of the seismic origin. Sites with an insufficient dataset are reported in grey.

The management of a large amount of observations was soon understood as the main challenge of the archaeoseismological fieldwork leading to several issues in terms of methodology and data analysis. Therefore, we decided to build a database that would allow storing the data in an orderly manner. A database speeds up indeed considerably the real-time data acquisition, facilitates its management and processing, guarantees the homogeneity of all of those input values (Anichini et al., 2012; Gattiglia, 2018), and reduces the risk of loss. The structure of the database itself enables faster researches and data mining. We based our program on the pioneer initiatives of the ACoR (Atlas des techniques de la Construction Romaine, <https://acor.huma-num.fr/>, last accessed July 25, 2021 - Dessales, 2020) and OPUR (Outil Pour Unités de Réparation) databases (ANR Recap: <http://recap.huma-num.fr/webpublic/#recap>, last accessed July 25, 2021), which aimed to register and characterize roman building techniques and ancient post-seismic repairs in Pompeii site (Dessales and Tricoche, 2018). While adopting a starkly different approach by focusing on damage, RISC benefited considerably from those previous projects, especially in terms of data structuration and data entry. The main objective was to conceive a database structure that would closely fit fieldwork requirements.

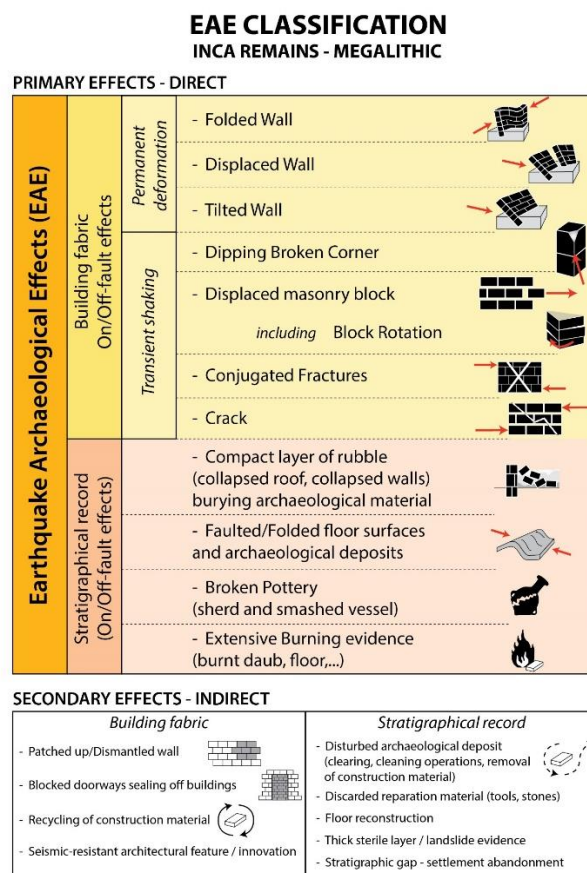


Fig.2. EAE chart adapted to Inca megalithic architecture (modified from Rodríguez-Pascua et al., 2011). Our fieldwork focused on the EAE affecting the building fabric, and due to off-fault effects.

4.2 A field-designed database with a single front-end user interface

We used the proprietary FileMaker Pro 16 software, which has the advantage of providing both the data storage and the user interface. Easy-of-use and ergonomic, thanks to its customizable interface, this Database Management System (DBMS) provides a particularly well targeted solution to meet investigation needs. Thanks to the FileMaker Go extension, freely available in any iOS device, database models are easily transferable and adaptable to the two main types of mobile devices (smartphone or tablet). The main advantage of those devices is to provide an interface wide enough to allow a direct digital entry during the fieldwork (Gattiglia, 2018). The use of a mobile device as the main tool for data collection required rethinking deeply the design of the user interface to address the specific fieldwork requirements (accuracy, simplicity, rapidity). We built, therefore, a straightforward database organized around one main table, the “Damage” table (Supplementary 2), and characterized by a sober and intuitive display. “Damage” gathers the main information relative to the core of the investigation topic, i.e., the EAE registered on the archaeological heritage (Fig.2). Moreover, we integrated basic information relative to the geographical and architectural context of the EAE.

The most suitable and easiest way to make RISC operative for users was to create one form composed of three distinct tabs (Fig.3). The first one, entitled “Context” includes basic data on the geographical and architectural environment of the EAE (Fig.4). The second tab focuses on the EAE description and characterization. Finally, the third one is dedicated to the illustration of the registered EAE (any type of visual representation). By means of those three tabs, the present form reproduces and supports the three main steps of the EAE record. It has turned into a single front-end user interface, simplifying the data entry. We made some other adjustments to make the interface as user-friendly as possible:

- A widespread use of thesauri and dynamic lists of values reduce the risk of data heterogeneity and the entry time. Four interdependent values lists, which feed into each other as data is entered, were inserted in the “Context tab”, enabling the database user to fill the tab according to a hierarchical tree (Fig.4 – Supplementary 2). Standardizing the dataset avoid creating future accidental discrepancies and speeds up hence the data analysis thanks to efficient queries.
- The automatized data entry for some metadata fields. Among others, that is the case for the dates of creation and modification of each record. They are directly managed by FileMaker and do not need any supervision.

- Script-writing dedicated to task automation such as the taking of picture or the GPS coordinates acquisition (Supplementary 2).

The current structure and design of the RISC database do not prohibit or impede future evolutions or extensions. The flexible nature of the database opens the door to substantial adjustments, providing solutions to other scientific needs and questioning.

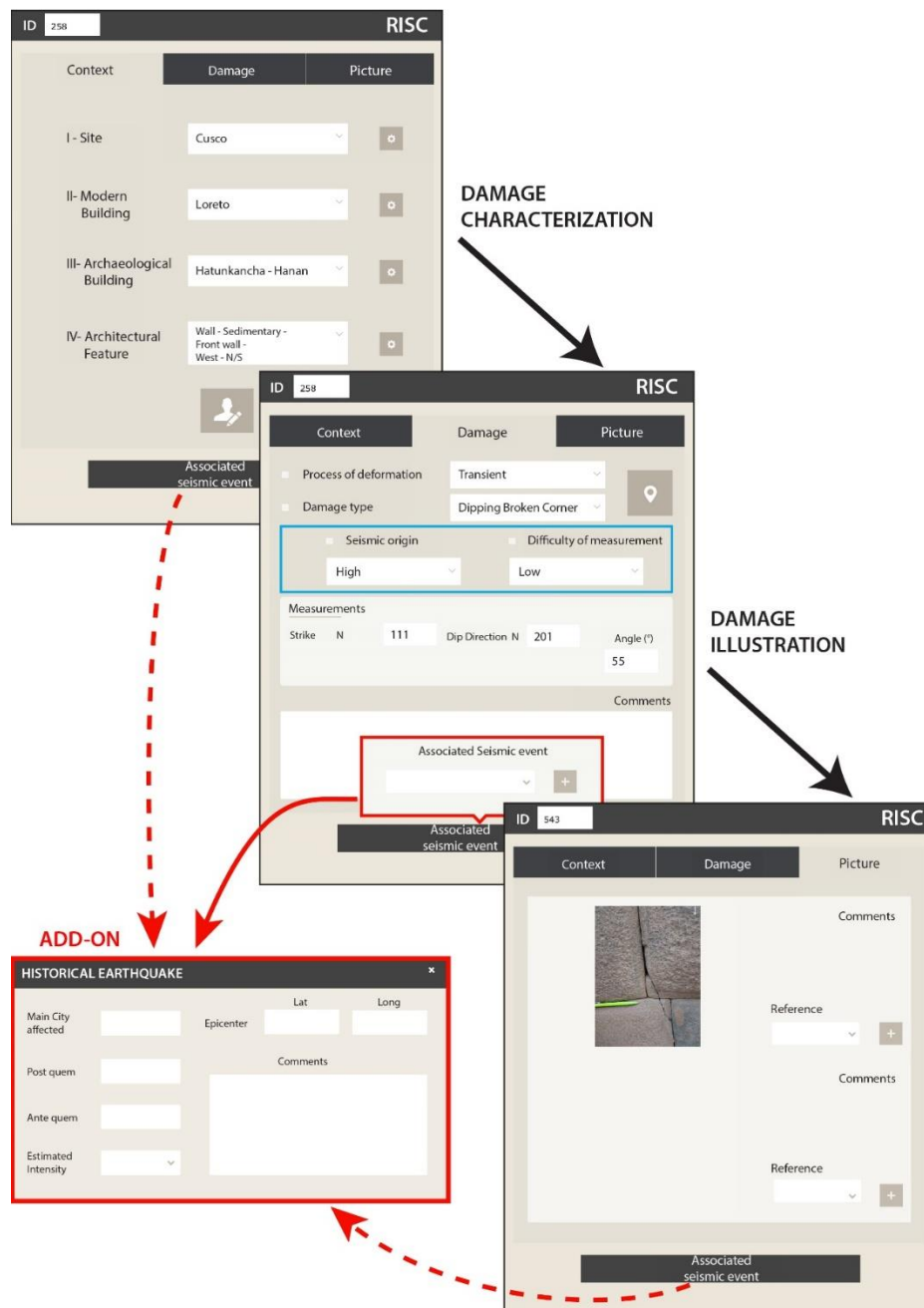


Fig.3. The RISC front-end user is organized around three tabs: “Context”, “Damage” and “Picture”. Those three sections reproduce the three main steps during the data acquisition. In blue: the two metadata fields to assess the data quality. In red: the database extension, which allows relating one EAE with a particular seismic event.

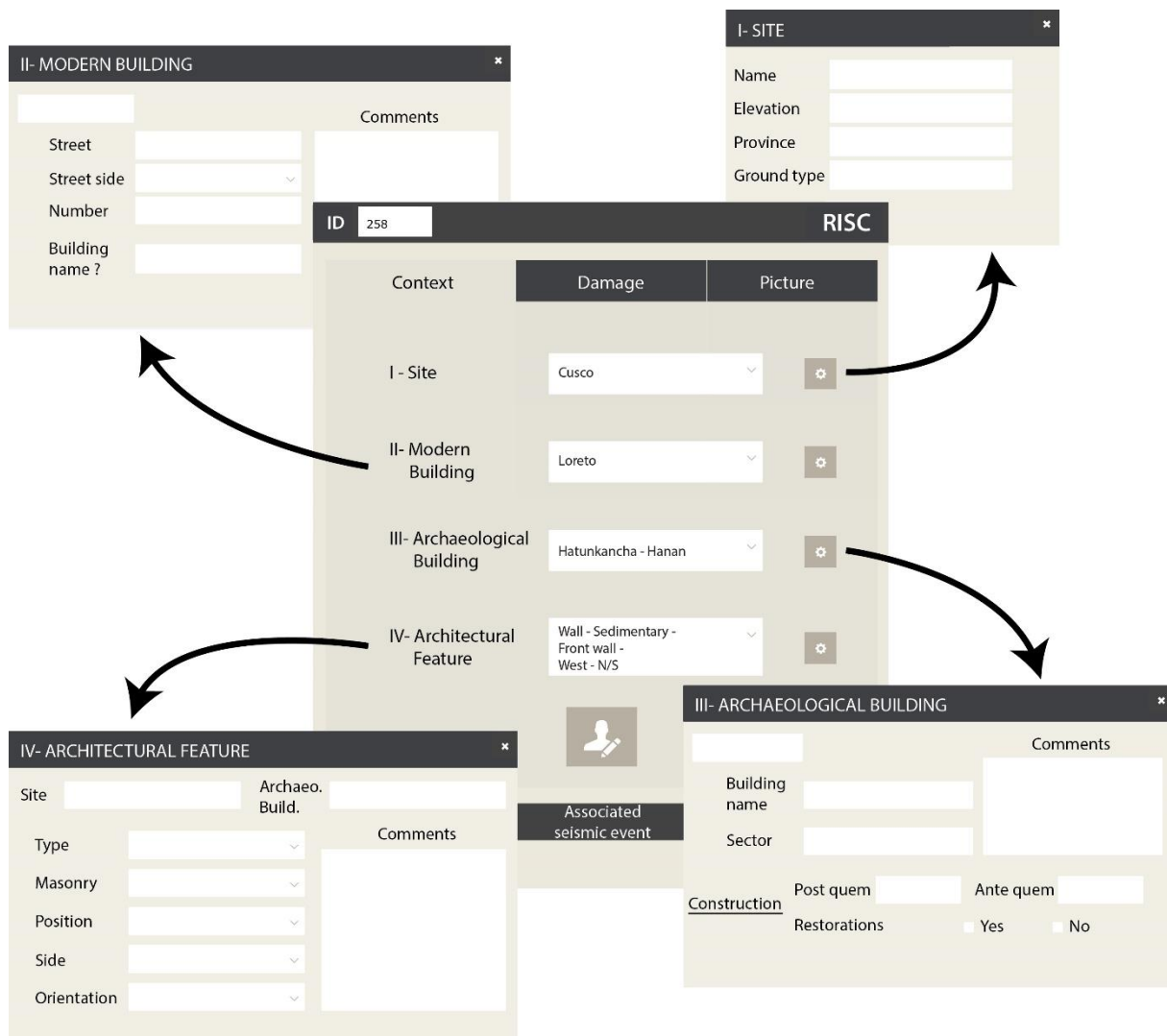


Fig.4. “Context” tab of the RISC front-end user interface. You may note the user-friendly structure based on interdependent values lists.

4.3 An adaptable and customisable tool enhancing the archaeoseismological methodology

Fieldwork procedures and methodologies are still too often unreported in the archaeoseismological literature, and it is therefore difficult for the reader to understand how the EAE and evidence were identified, ranked and interpreted (Galadini et al., 2006). The development and design of a database in the framework of the project RISC came with an automation of the data recording and enabled, thus the creation of additional fields that may improve substantially the data quality and its assessment.

Recording architectural damage referred to as “Earthquake Archaeological Effects” does not mean in any way that the potential non-seismic causes are completely ruled out from the scientific discussion. That is the global quality of the dataset and level of confidence in the

archaeoseismological observations, as a statistic assessed through metadata fields, that allows discussing the potential impact of past earthquakes at the scale of an archaeological site or even a region (Giner Robles et al., in press; Giner-Robles et al., 2011 - Fig.1b). That is why such a database would be an important first step towards studies on paleo- or historical earthquakes on a peculiar architecture such as the Inca monuments.

To meet the requirements of both data assessment and fieldwork, we considered a qualitative assessment based on clear and simple criteria as the most adapted and effective solution. We created two metadata fields (Fig.3) based on a list of values and containing four probability and confidence levels (“Low”, “Medium”, “High” and “Certain”). We originally created one metadata field, whose objective was to assess the level of confidence in the seismic cause of the damage (Fig.1b – 1 in Table 1). We introduced then a new one related to the difficulty of characterizing the recorded EAE. This field addresses the different measurement biases and gives the reader a qualitative estimation of the uncertainty of the measurements and observations.

The filling of the second metadata field (2 in Table 1) is based on a limited number of criteria (accessibility to the architectural feature, presence of vegetation cover as well as alterations, posterior to the damage that makes difficult the observation and characterization). On the other hand, the interpretation of the seismic cause of the damage (1 in Table 1) depends on several indicators:

- The masonry type (rustic, cellular, cyclopean, polygonal and sedimentary – Agurto Calvo, 1987). Those different categories are directly related to different rock types (calcareous/andesite/granite) and distinct layouts (forms and types of courses). They have therefore different vulnerabilities to slow deterioration processes. For instance, the rustic masonry type in Inca architecture is highly vulnerable to a large spectrum of deterioration processes (dissolution, vegetation growth, physical weathering and alteration) that makes it more difficult to distinguish effects related to climatic processes from damage induced by seismic shaking;
- the damage aspect and dimension;
- the petrological and geological contexts (water ingress in the architecture, slope instability, soil and rock properties and structural weaknesses);
- the management of the archaeological site (site history and large restoration works).

Based on the presence or absence of “positive” criteria, it is possible to assign a specific level of confidence for each recorded EAE. This method allows assessing quickly the quality of the archaeoseismological data at the site and regional scale.

Due to the unpredictable and changing nature of the fieldwork, the database has to be adjusted and improved frequently following an iterative process. Those improvements originate principally from the trial and error process (back and forth between field and laboratory). However, the DBMS offers great flexibility making it possible to cope easily with superficial and structural changes. Database extensions do not alter the current functioning and do not necessarily induce large modifications of the front-end user interface. The particularity of FileMaker databases, able to run on both fixed and mobile devices, constitutes a great opportunity to imagine and test new database versions on a computer without modifying the operative version available on tablets during the survey work (Endnote 1). As an example, we developed the first extension to indicate a potential causal relationship between one particular seismic event and the recorded EAE. This add-on takes form through an additional and optional button in the bottom part of the main interface. Clicking on this button will lead the user to select one existing seismic event related to the architectural damage recorded if or when known or will guide him to create a “new” event responsible for the damage (Fig.3). Besides its utility in distinguishing EAE produced by distinct past earthquakes (the chronological assumption will require bibliographical and/or historical sources – Rajendran et al., 2013), the extension may prove to be particularly relevant during a survey carried out immediately after a future destructive seismic event (Cancino, 2011; Davis et al., 2019). This particular case demonstrates how much the current RISC database might be enlarged and upgraded in the near future to address new scientific issues.

Regarding RISC perspectives, we should consider several shortcomings and feasible improvements. The creation of a well-organized dataset of earthquake-induced damage on archaeological sites of the Cusco region has one fundamental implication: the reproducibility of the archaeoseismological investigation enabling the periodical update of the information while keeping track of previous recordings as an indicator of potential changes (Van Balen, 2017). Taking into account this change in outlook induces a substantial widening of the database scope and opens the door to interesting adjustments. We could only mention some of them: new fields dedicated to the qualitative estimation of the global state of conservation of the architectural feature and indices assessing the level of structural risk caused by the EAE. Furthermore, we may consider enhancing the temporal dimension of the EAE recording as a means to make the database even more suitable for periodic archaeoseismological surveys.

We developed RISC as a user-friendly program to support and strengthen our archaeoseismological project. The intrinsic properties of databases, coupled with the results of the archaeological survey, suggest a broader interest covering several DRR stages in the cultural heritage conservation program.

EAE	Level of conf.	1 -SEISMIC ORIGIN					2 –MEASUREMENT BIAS
		Masonry Type	EAE characteristics	Aspect	Geological Context	Human Context	
Dipping Broken Corner	Low	Rustic Cellular Cyclopean Polygonal Sedimentary	Plane < cm Dip angle <25° Ultimate course of masonry	Plane hardly definable	Pre-existing rock fractures within the block	Cleaning work	Difficult to access Irregular plane Low dip angle Vegetation
	Medium	Cellular Cyclopean Polygonal Sedimentary	Plane > cm Dip angle >25°	Clean Plane	X	Cleaning work	Irregular plane
	High	Polygonal Sedimentary	Plane > cm Dip angle >25°	Clean Plane	X	X	X
	CERTAIN	DOCUMENTED DISORDERS (pictures or scientific literature)					
Displaced masonry block	Low	//	Small and unique Ultimate course of masonry Non constant displacement	Mortar masonry	Slope instability Water ingress	Restoration work Unfinished Structure	Heterogeneous displacement
	Medium	//	Non constant displacement	Dry joint masonry	Water ingress	Restoration work	Heterogeneous displacement
	High	//	X	Dry joint masonry	X	X	X
	CERTAIN	DOCUMENTED DISORDERS (pictures or scientific literature)					
Fracture - Crack	Low	Rustic Cellular Cyclopean Polygonal Sedimentary	Affecting 1 rock	//	Slope instability	Large-scale repairs	Non-apparent fracture plane Irregular plane Vegetation
	Medium	Cellular Cyclopean Polygonal Sedimentary	Affecting more than 1 rock	//	X	X	X
	High						
	CERTAIN	DOCUMENTED DISORDERS (pictures or scientific literature)					
Block Rotation	Low	//	Ultimate course of masonry	//	Slope instability	Unfinished Structure	Small movement (<2°)
	Medium	//	X	//	X	X	X
	High						
	CERTAIN	DOCUMENTED DISORDERS (pictures or scientific literature)					

Table 1. Two metadata fields, providing a level of confidence in 1- the seismic origin of the damage and 2- the measurement precision and difficulty, were added to the database interface. This table summarizes the main criteria used for the most common EAE types registered during our survey. Those criteria determine the level of confidence based on a qualitative scale ranging from “Low” to “Certain”. “//” : the criterion does not apply to this EAE type ‘X’ : no « positive » criterion ‘Row in grey’: confidence level not registered.

5. Results and discussion

5.1 Facilitating archaeoseismological survey

The archaeoseismological survey carried out within the Cusco area involved nine persons during two field campaigns. Those two campaigns of three months in total led to the inventory of more than 5000 architectural features in 17 archaeological sites (Fig.1a). The implementation of a tailor-made database contributed to improving significantly the speed and efficiency of the fieldwork. Three semi-automatized and multifunctional entry processes were particularly useful: the creation of several dynamic lists of values, the connection between several tablet functions and the database (GPS, camera...), and the possibility to duplicate the DBMS on several tablets without affecting the data homogeneity. Working in pairs was particularly well-suited and productive. As an illustration, one pair was able to register more than 100 EAE in only a half day of work in PISAQ settlement. Even if it depends obviously on the density of seismic damage in Inca buildings, it shows how RISC brought powerful support to the data acquisition (detailed and accurate).

The database not only fastens the entry time it also allows a standardized data quality assessment. Although qualitative, both metadata fields we imagined to assess the data quality enable evaluating the archaeoseismological potential for each site visited as well as the precision for each single EAE record (measurements and observations). At the time of the archaeoseismological survey, the database included only one metadata field (See 4.3). The results of the data quality provide interesting results about the relevancy of the archaeological sites datasets. In three of the 17 archaeological examined, the sample was too small ($n < 20$) and/or involved an insufficient proportion of medium and high-quality indices ($< 50\%$ - in grey in Fig.1b). Although we considered, in the frame of our study, those three sites as irrelevant for the archaeoseismological interpretation, all the data will be stored and will remain available for future purposes. The confidence indexes represent valuable feedback for future investigations in the same area, necessary to carry out better-targeted surveys.

Archaeoseismological methodologies are particularly dependent on the type of architecture and thus EAE that professionals may encounter. The typologies as well as the identification criteria have to fit the geographical and cultural context and the research needs, influencing the database content and interface. While the database conception needs to be tailor-based, we consider that the structure of our database may be a helpful template for other researchers in South America and an off-the-shelf system in case of an earthquake.

5.2 Re-assessing the seismic hazard in the Cusco region

The archaeoseismological approach carried out in Cusco highlighted numerous seismic damage on Inca architecture along the Sacred and Cusco valleys. Through statistical and qualitative analysis detailed in 5.1, survey records stored in RISC were quickly processed. We concluded on the undeniable presence of EAE in 14 archaeological sites of the area (Fig.1). Although further research is required to date the EAE registered and assesses earthquake recurrence; preliminary results demonstrate an unexpectedly large impact of ground motions. The wide distribution and common occurrence of EAE argue for a drastic reappraisal of the (pre)historical seismicity in that region, seismicity that was underappreciated before. Several Inca remains located in the Sacred valley display seismic damage (e.g., Machu Picchu, Ollantaytambo, Huchuy Qosqo and Písaq), contrasting indeed with the low level of seismic activity during the instrumental era (Fig.1a – Supplementary 1) and contradicting past statements on the seismic vulnerability of Machu Picchu (Carlotto et al., 2007).

The dating of EAE is still a critical point when dealing with poorly contextualized remains. It requires crossing approaches to complement the archaeoseismological data. That is why we develop additional detailed tables, including architectural, archaeological and seismological information. Those linked tables do not only contextualize EAE in their build environment, they also foster the multidisciplinary collaborative effort around this specific topic. Immediately after the archaeoseismological survey or during the post-processing, the user has the possibility to add data about the dating and characteristics of archaeological buildings or past seismic events found in the scientific literature. This accretionary process of data input/storing increases substantially the cross-disciplinary potential and leads to a better involvement of archaeological, architectural, and paleoseismological results into the final interpretation.

Finally, the RISC database contributed substantially to the reassessment of the seismic hazard in the area thanks to its spatial dimension. The GIS compatibility of the database outputs (spreadsheet files) enables quick visualization of the EAE distribution at a regional scale and within a studied site. Looking at the global distribution and density of EAE exhibits a clear pattern: a stronger seismic impact in the Eastern part of the Sacred Valley and the core of the Cusco valley (Fig.1a). Refining this data will allow maybe to identify a common seismic source responsible for the damage. Similarly, the precise maps derived both from the geolocation (Fig.5a) and the detailed architectural context available for each record are the starting point for in-depth inspection of damage. Including complementary data on the previous restoration

works as well as indications on surveyed/non surveyed areas, we might consider identifying sectorial patterns. Understanding what buildings were the most affected and for what reason will open the door to the identification of vulnerability factors and local site effects (Brando et al., 2019). The organized and comprehensive dataset gathered by the database enables, even, a precise mapping of the EAE at the building scale (Fig.5b). This multi-scale analysis enhances considerably the archaeoseismological interpretation and constitutes a prerequisite for periodic inspections.

As we demonstrated in 5.1 and 5.2, RISC was designed as a powerful tool to support two main phases of the seismic hazard assessment: the data collection and the past earthquake characterization. Bearing in mind that the most profitable way to assess the vulnerability of a historic building is the analysis of the consequences induced by the previous earthquake in its fabric (Cancino, 2011; Feilden, 1987), the database may have a crucial role in strengthening the risk preparedness in archaeological heritage programs.

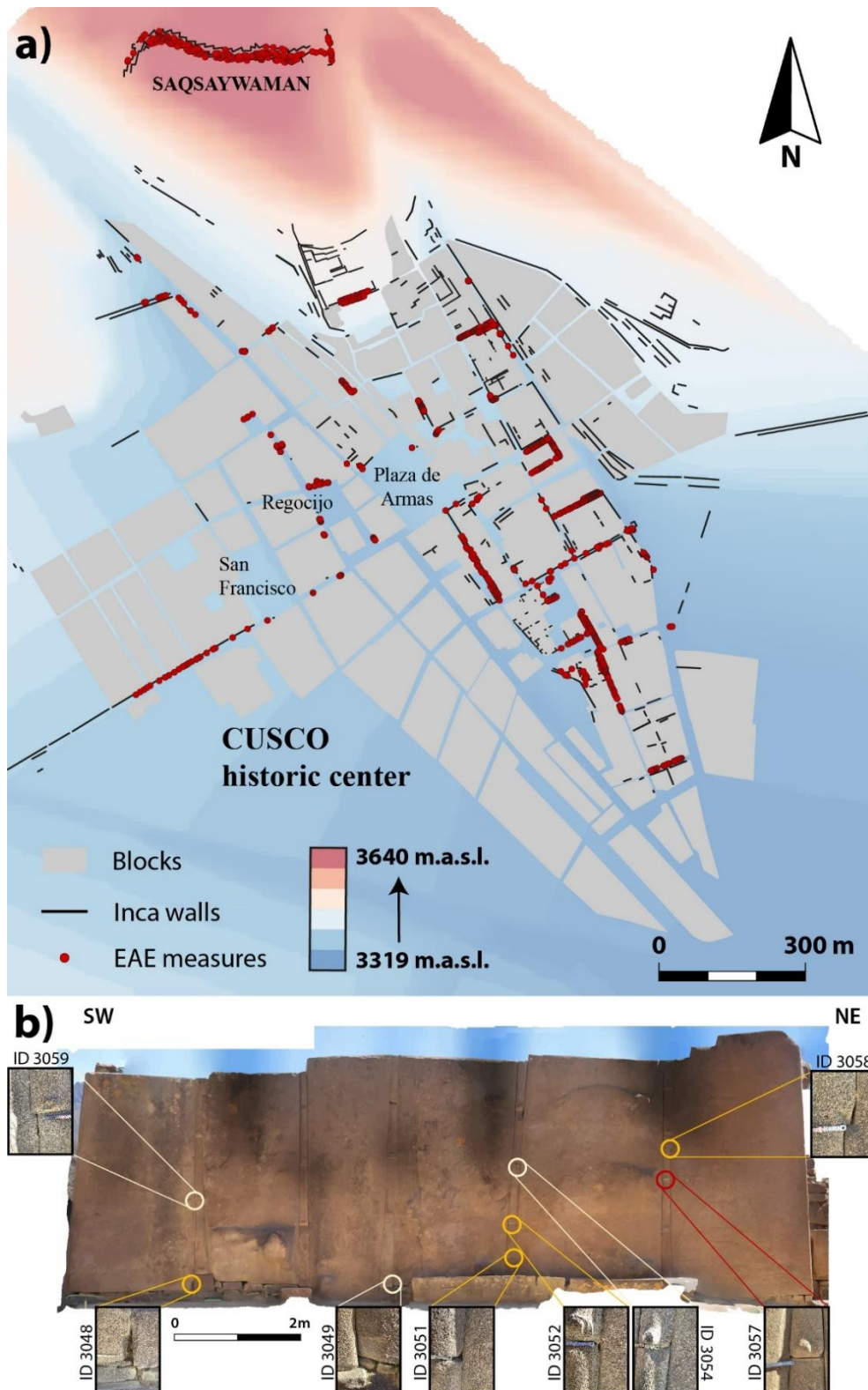


Fig.5. a) Spatial distribution of the EAE (red dots) in the archaeological settlements of Cusco and Saqsaywaman. Credits DEM and Inca walls: Instituto Nacional de Cultura, Center for Advanced Spatial Technologies (Univ. of Arkansas) & Cotsen Institute for Archaeology (UCLA); b) Distribution of the EAE on the Sun Temple of Ollantaytambo. The color indicates the probability of the seismic origin (beige: Low; orange: Medium; red: High).

5.3 Monitoring the archaeological heritage

Initially, our archaeoseismological survey was conceived as an *ad hoc* data acquisition, i.e. responding to an academic project completely disconnected from current heritage vulnerability issues. Archaeoseismologists have developed though a specific expertise in architecture that can benefit considerably to heritage stakeholders and curators.

Considering converting the “casual” survey into a systematic and periodic inspection requires taking into account preservation concerns and rethinking completely the whole potential of our approach. Although the current objective of RISC is to record and inventory seismic damage only, this type of structural alteration may constitute important weaknesses in the building fabric, sensitive to other destructive processes (erosion, landslides, human actions ...). The dataset obtained in the framework of an archaeoseismological research project turns out, therefore, to be an *ad hoc* condition assessment of the archaeological heritage (Fig.6). It brings valuable information on the state of conservation of the buildings and calls for a regular implementation of such analysis. The database is, in that sense, a promising tool for monitoring the state of conservation of the building and preventing potential deterioration of the structure. As previously mentioned in 4.3, the database structure might be easily improved to take into account this temporal dimension in the data acquisition.

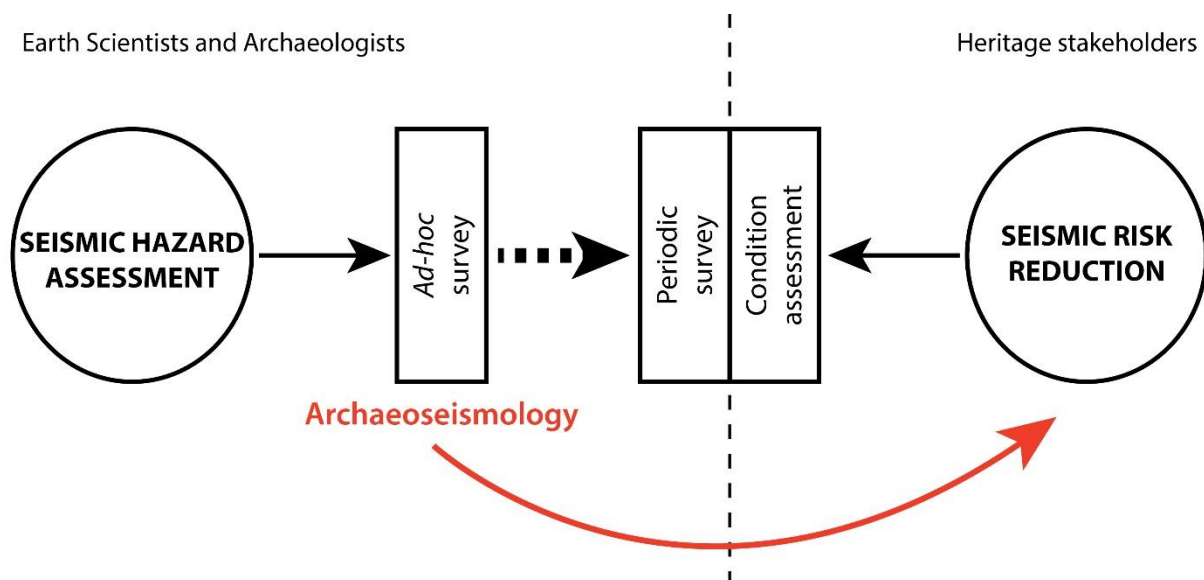


Fig.6. Diagram summarizing the theoretical disconnection existing between two worlds: heritage conservators and academic scientists. From our point of view, archaeoseismology can provide an interesting tool to engage collaboration and dialogue.

According to previous studies, some 50 percent of the damage during an earthquake is directly related to the lack of maintenance (Feilden, 1987). If this figure does not address the situation for the cultural heritage, in particular, the incidence of too scarce and/or inappropriate conservative works was yet emphasized as a major vulnerability factor (Brando et al., 2019; Cancino, 2011). Based on the frame of reference that constitutes the *ad hoc* inspection and based on the seismic hazard data provided by the archaeoseismological approach, two critical DRR phases may benefit from the present methodological tool: the monitoring pre- and post-intervention (Fig.7). Once a large dataset has been collected and has been made available, it converts into relevant support for assessing the evolution of the archaeological remains state and for proposing new conservation plans. Similarly, the inspections conducted with the database will contribute to evaluate the positive or negative impact of potential retrofitting works. We are thus convinced that an archaeoseismological database like RISC has a role to play in helping to quantify the threats, scaling the prevention measures and controlling their effects (Fig.7).

In heritage conservation, vulnerability analysis results too often in complex and resource-consuming procedures (Canuti et al., 2005; Ravankhah et al., 2019), leading to an ever-widening gap between academics and heritage curators/decision-makers. In emerging economies like Andean countries, for which cultural expenditure may represent a low priority investment, it is even more essential to select the most appropriate and frugal mitigation option, resulting from a subtle balance between implementation/maintenance costs and benefits (ICCRROM, 2004; Paolini et al., 2012). Minimally invasive, easily and quickly implementable, low-cost strategies and low-tech devices represent a pragmatic way to cope with immediate and urgent conservation threats, as yet acknowledged for photogrammetry (Abed et al., 2017; Dhonju et al., 2017; Remondino and Rizzi, 2010). The good cost-benefit ratio that generally characterized those methods contributes thus to reopen a fruitful dialogue and collaboration between parties with divergent concerns. We believe that RISC database is one relevant example of a multifunctional, flexible and easily replicable assessment strategy that could be implemented in archaeological sites throughout the Andes. The great amount of information accumulated during the monitoring process facilitates the prioritization of the interventions (Sevieri et al., 2020) and serves as comprehensive support for decision-making. The international community now considers risk preparedness and DRR as a priority (UNISDR, 2015). Hence, databases like RISC have to play a role in transforming heritage conservation into a day-to-day effort, financially sustainable.

As Feilden (1987, p. 19) pointed legitimately: “after an earthquake, a precise knowledge of every historic building and its contents is one of the most crucial factors in making an accurate assessment of the damage and conservation work required”. We strongly support that archaeoseismological databases represent a relevant tool to acquire, store and process this type of architectural and structural knowledge. RISC established that organized datasets might be particularly helpful during three specific steps of the Seismic Risk Management cycle: condition assessment, past seismicity characterization and heritage supervision.

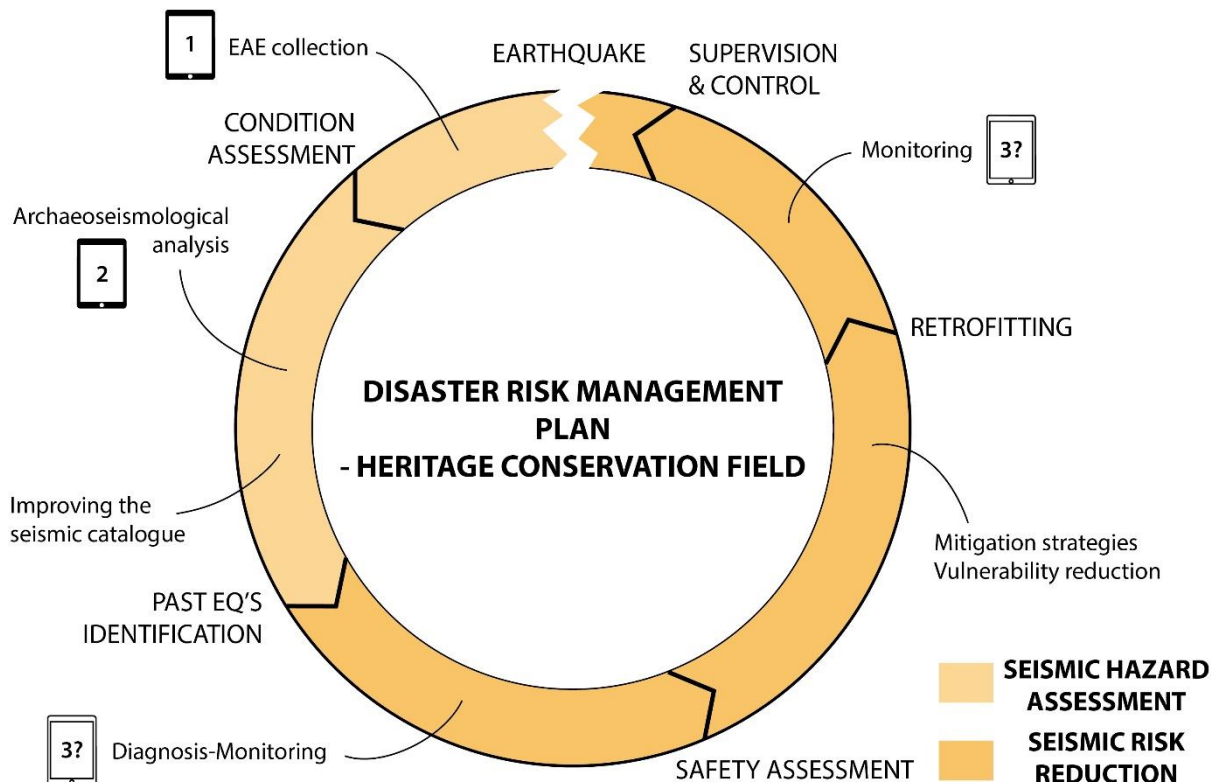


Fig.7. Graphical representation of the Disaster Risk Reduction program applied to heritage conservation and inspired on the Preventive Conservation Cycle (principles formulated by the ICOMOS Charter (ICOMOS, 2003). RISC project demonstrates the role that may play database systems during four stages of this cycle.

Conclusions

Despite the challenges and difficulties, there is an absolute necessity to involve more deeply science in risk assessment topics and better communicate results to the public and decision-makers (Stewart et al., 2018). Research methodologies and approaches may contribute notably to raise awareness about the seismic threat on cultural heritage and support adapted DRR

programs. Monitoring archaeological site has turned to be a key stage in implementing proactive measures to face the seismic hazard. It also constitutes a meeting ground for a wide spectrum of specialists and an excellent opportunity to carry out integrative and multi-disciplinary analysis (ICCROM, 2004; Stovel, 1998; UNISDR, 2015).

We are convinced that archaeoseismology, situated at the crossroads between seismic and vulnerability studies, has to take part in this multi-sectoral approach in heritage preservation. By providing all the necessary information about the RISC database, we hope to share a relevant template for future archaeoseismological investigations in the Andes, and more broadly, in all emerging countries. This user-friendly way of storing and organizing data improves the data entry and processing and considerably facilitates data sharing (Labrador, 2012).

RISC database does not represent only advancement in implementing large semi-quantitative approach in the Andes. It also demonstrates how a basic data collection system might become a relevant interface for a systematic and periodic condition assessment. A properly selected and organized dataset may play a central role during archaeological remains supervision and may serve as a basis for disaster risk management (Heras et al., 2013; Paolini et al., 2012; The Getty Conservation Institute, 2015). Given the humanitarian stakes during a seismic crisis, in-depth assessments of built heritage integrity are usually carried out at the end of the emergency phase. However, quick on-site damage analysis allows the identification of risks posed to both cultural heritage and the populations in the aftermath of a disaster. Easy to deploy after a seismic crisis, such a database would constitute a unique asset that would benefit any immediate action undertaken to inventory damage in endangered cultural heritage and evaluate the effects of those emergency measures prior to retrofitting works. Hence, easy to implement and customize, our database prototype seems to be a promising complementary tool to monitor archaeological sites, especially in emerging countries where low-tech devices constitute the most appropriate and cost-effective solution (The Getty Conservation Institute, 2015).

Endnote

- 1) We are aware that the usability of proprietary software such as FileMaker Pro may represent a limit to the promotion of the RISC database, especially in developing countries. However, only one license is needed to design the database that may be then replicated freely in as many iOS portable devices as necessary (FileMaker Go is a free app). Furthermore, based on the conceptual and physical models of the database presented in detail in this work (Supplementary 2), any reader interested in building a similar database will be able to do it as an open-source option.

Acknowledgements

This work would not have been possible without the cooperation of the Decentralized Department of the Ministry of Culture from Cusco and the Geopark of Machu Picchu. We also thank Léo Marconato, Lorena Rosell, Peter Molnar, Sara Neustadt, Fabrizio Delgado and Xavier Robert for their precious assistance during the field campaigns. The authors would like to express their gratitude to H el ene Dessales for her enthusiasm in sharing her feedbacks on the ACoR database as well as to Philippe Garnier for his constructive proofreading. This work was part of the CuscoPATA project (006-2016-FONDECYT) and of the inter-institutional agreement between IRD (Institut de Recherche pour le D veloppement) and INGEMMET (Instituto Geol gico, M nero y Metal rgico del Per ). This work has been realised in the framework of the IDEX CDP Risk@Univ. Grenoble Alpes as part of the program ‘‘Investissements d’Avenir’’ overseen by the French National Research Agency (ANR-15-IDEX-02). The project has received, as well, financial support from the CNRS through the MITI interdisciplinary programs and from the IRD.

Appendix Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jsames.2021.103447>.

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