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The contribution of post-earthquake field reconnaissance missions to improving seismic safety

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Abstract

Post-earthquake reconnaissance missions have been systematically undertaken since the 1960s by a variety of national and international teams of earthquake especialists, notably from UNESCO (1963-1980), the California based Earthquake Engineering Research Institute (EERI), by the Architectural Institute of Japan (AIJ) and the Japanese Society for Civil Engineering (JSCE), by EEFIT in the UK, AFPS in France and others. These missions, beyond adding to global understanding of earthquake effects and ways to mitigate them through design, all have in addition the aim of communicating to those in the affected country the need for increased earthquake awareness and suggesting appropriate responses to improve seismic safety in the countries visited. This can be done, for example, by involving local specialists (engineers and scientists) in the mission teams, giving advice on the development of local building codes and on reconstruction, focussing part of the field effort on the study of vernacular housing and other special local problems, and by making the results of the investigation widely available for follow-up investigations. This paper will review the extent to which past earthquake field missions have contributed to the improvement of seismic safety globally, and will consider ways in which future field missions might be more effective.

Keywords: Earthquake Field Reconnaissance Missions; earthquake damage; vernacular housing; historic buildings; recovery

1. Introduction

It is now generally accepted that post-earthquake field investigations have made, and continue to make, an enormous contribution to our understanding of the mechanics of earthquakes, the ground motions they produce, and their effects on buildings and other structures and on society at large. Ambraseys [1] , one of the pioneers of today's programme of earthquake field investigations wrote:

> "It is increasingly apparent that the site of a damaging earthquake is undoubtedly a full-scale laboratory, in which significant discoveries can be made by keen observers - seismologists, geologists, engineers, sociologists and economists. As our knowledge of the complexity of earthquakes has increased we have become more and more aware of the limitations which nature has imposed on our capacity to predict, on purely theoretical grounds, the performance of engineering structures, of the ground itself or of a community. It is the long-term study of earthquakes and fieldwork that offers the unique opportunity to develop a knowledge of the actual situation created by an earthquake disaster"

Henry Degenkolb, who as President of EERI was instrumental in setting up the Learning from Earthquakes Programme expressed essentially the same point in a different way [2] :

> "Some of us argue that you shouldn't get your structural license until you've chased an earthquake. No matter how much you have read the reports, the impact doesn't strike you until you've seen the damage"

The contributions which post-earthquake reconnaissance missions have made to the development of earthquake science and earthquake engineering have been well-documented. They have enhanced our understanding of the distributions of ground motion, the effects of soil amplification, geotechnical process and the types of failure which are found in structures constructed with a range of different materials and typologies [3,4]. They have been intended to, and have contributed greatly to, the development of codes and construction practices, particularly in the countries which have organised and funded these field missions.

But the field missions have also had, implicitly or explicitly, the aim of reducing the impact of earthquakes globally and specifically in the countries which have played host to these missions. These have often been the lower-income countries, where the human toll from earthquakes has not only been far greater than in the richer countries, but also has stayed at a very high level, with little reduction in death rates over recent decades [5].

The 1962-1980 UNESCO Missions for example had the aim "to investigate the cause and effects of such events for the purpose of adding to scientific and practical knowledge for the mitigation of their disastrous consequences" [6]. The EERI's Learning from Earthquakes (LFE) programme was formalised in 1973, with three principal activities: conducting field investigations; developing guidelines for conducting post-earthquake investigations that enable consistent data to be collected; and disseminating the lessons learned [7,8] (both in the USA and internationally). And the constitution of the UKs field reconnaissance team EEFIT states that its aims are "to collaborate with colleagues in earthquake-prone countries in the task of improving the seismic resistance of both traditional and engineered structures".

This paper aims to consider to what extent post-earthquake reconnaissance missions have contributed to global seismic safety, with particular reference to the improvement of seismic resilience in the countries where earthquakes and their impacts have been investigated. The paper begins with a brief historical survey of the development of post-earthquake field missions over the last 60 years; it then looks at some ways and some specific areas in which the learnings from field missions can be claimed to have influenced practice and contributed to seismic safety globally. It concludes with some suggestions for ways in which the planning and organisation of field missions can be modified to improve their long-term value for the regions studied.

2. Achievements of field missions since 1960

2.1 UNESCO Missions 1960-1980

Over period of nearly 20 years from 1962, UNESCO supported at least 23 post-earthquake reconnaissance missions. Their locations are shown in Figure 1. Nicholas Ambraseys was the leading figure in this programme. The missions were interdisciplinary, involving both engineers and earth scientists, and where possible were joined by local specialists in the country affected. They aimed to be in the country within 72 hours of the event, though that was never achieved, and more typically 2-3 weeks or more elapsed from the time of the event to the arrival of the team; however, once in the country, the mission typically spent 3-4 weeks on the investigation, longer than is nowadays usual [9].

The missions observed and recorded details of visible surface faulting, liquefaction and landslides, any ground motion recordings collected, and the performance of buildings of different types. The objectives and style of operation depended on the conditions found. They were, arguably, the first to describe in detail the performance of adobe and rubble stone masonry buildings in Turkey, Iran and Pakistan; the first to note the significantly better performance of stone masonry buildings whose roofs were independently supported on timber columns (1974 Pattan earthquake in Pakistan); the first to systematically investigate the performance of historic masonry buildings (in the 1976 Friuli earthquake) and report on the effectiveness of simple metal tie-rods in limiting collapse; and the first to note the poor performance of mid-rise reinforced concrete buildings under shaking with a high amplification in the 1-2.5 sec range (in Bucharest in the 1977 Vrancea earthquake).

As UNESCO-funded missions, the reports also made recommendations to the Governments of the affected countries. These routinely included advice on the requirement for improved building design practice, supported by development of local codes; the need for careful assessment and repair of damage structures; the need for a proper plan for reconstruction (taking account of experiences in other earthquake-affected countries); and the need for capacity building, through training programmes and the development of institutions for education for earth scientists engineers and architects. It is not known how far these recommendations were influential, though at least in Skopje, the now internationally well-known Institute for Earthquake Engineering (IZIIS) was founded following the 1963 earthquake, and UNESCO did follow up their missions with seminars and training programmes in several countries. It was also claimed that the UNESCO missions, as well as adding significantly to our knowledge of earthquakes and their effects, also helped to understand “ways and means of mitigating such disasters through the use of local building materials and methods of construction” [9].

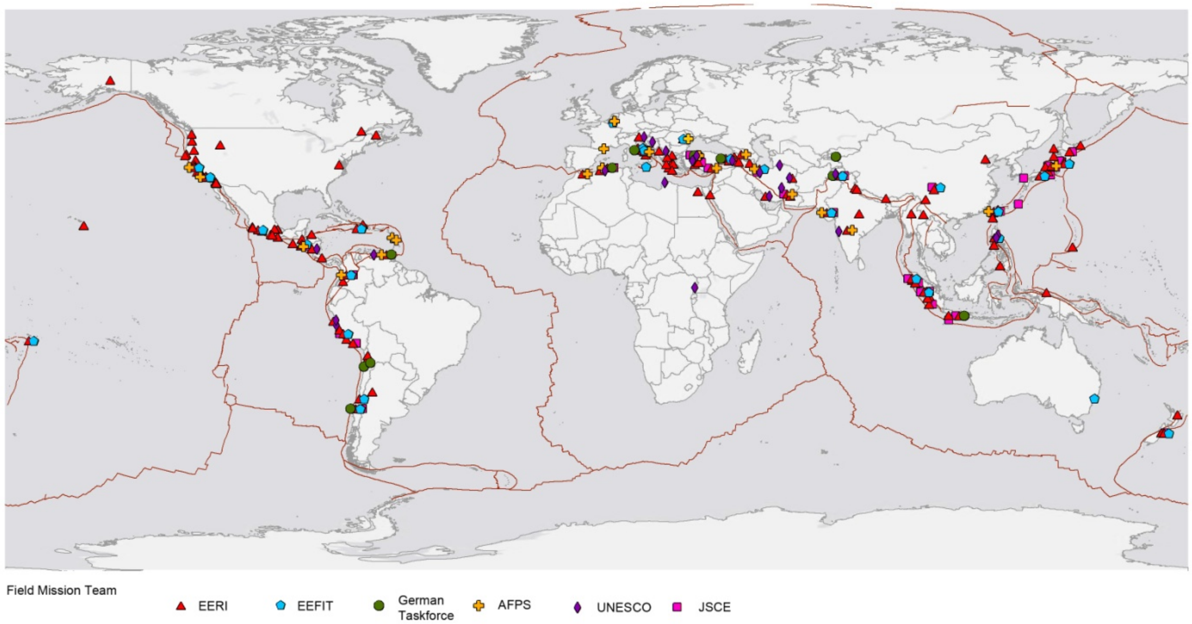

Figure 1. Locations of field investigations by different reconnaissance teams 1962 to 2013.

2.2 EERI Learning from Earthquakes Programme (since 1972)

The Earthquake Engineering Research Institute, based in Oakland California, was founded in 1949, and has conducted post-earthquake field investigations, both of US and non-US earthquakes from its inception. The 1971 San Fernando earthquake provided the stimulus to establishing EERI's Learning from Earthquakes (LFE) programme; it became clear from that event that advance planning and coordination would have been beneficial to achieve the maximum benefit in understanding the damage, ensuring all aspects were covered and avoiding contradictory reports from special interests [2]. The LFE programme was formalised in 1973, with three principal activities: conducting field investigations; developing guidelines for conducting post-earthquake investigations that enable consistent data to be collected; and disseminating the lessons learned [7,8]. Today, after mounting investigations of over 300 events, EERI has developed a highly professional approach to the mounting and management of field missions, and is undoubtedly the world's leading earthquake field investigation organisation. With a large worldwide individual membership, EERI is in many respects an international organisation with a global outreach.

By mid 2016, the total number of field missions of all types conducted by EERI since the 1971 San Fernando earthquake was 303, of which 141 have led to Reconnaissance Team Reports or Earthquake Spectra articles. Of these only 35 were in the USA, Canada or Mexico, the remaining 106 were elsewhere in the world. On average there have been about four such missions per year since 1990. The locations of the EERI earthquake reconnaissance missions are shown in Figure 1. The cumulative learning from all of these field missions is immense and includes many hugely significant contributions to geotechnical engineering, structural engineering, lifeline engineering and to the understanding of human responses in earthquakes and recovery processes. An early review was made in the publication *Reducing Earthquake Hazards* [7], and learning was more briefly reviewed in *Learning from Earthquakes* [4].

Unlike UNESCO, as a research organisation, EERI has not sought to make explicit recommendations to the affected countries in its reports; rather, it sees its international outreach as being through the accumulation and dissemination of post-earthquake reports and observations, and through cooperation at an individual level with local scientists, engineers and policy-makers. Indeed as an international organisation it has members in over 70 countries, including large cohorts of members in several of the lower-income high risk countries, notably India, Pakistan, and Colombia. EERI draws on its members in the affected country to form the basis of the EERI mission, including often the team leader. By creating these individual collaborations, it creates a community of individuals in the affected countries who can draw on the EERI documentation and resources to influence policy and practice and develop education programmes in those countries.

Although the primary beneficiaries of the LFE programme have been the earthquake engineering community in the USA, the documentation of the EERI earthquake reports contain many observations by individual team members, which have led to a gradual development of ideas about "best practice". This indeed may be a better way to disseminate the results of field missions than specific recommendations.

2.3 The UK Earthquake Engineering Field Investigation Team (EEFIT) since 1983

In 1982 EEFIT was formed as "a UK-based group of engineers, architects and scientists who seek to collaborate with colleagues in earthquake-prone countries in the task of improving the seismic resistance of both traditional and engineered structures". From the outset EEFIT was envisaged as a collaboration between academic institutions and the practising engineering profession. EEFIT exists solely to facilitate the formation of investigation teams which are able to undertake, at short notice, field studies following major damaging earthquakes and to disseminate the findings to engineers, academics, researchers and the general public. The objectives are to collect data and make observations leading to improvements in design methods and techniques for strengthening and retrofit, and where appropriate to initiate longer-term studies. Field training for engineers involved in earthquake-resistant design practice and research is also one of its key objectives.

Since 1982 EEFIT reconnaissance team have visited and produced reports on 29 separate earthquakes, including many of the most significant events of the period worldwide, with two of these (2009 L'Aquila and 2011 Tohoku) having had follow-up missions. The locations are shown in Figure 1. Eight of these events have been in the wider European area. Collaboration with other national teams has been an important feature of these missions where possible, and EEFIT has collaborated with teams from France, Italy, Turkey, USA, Chile, Peru and New Zealand. The findings of EEFIT reports parallel, in many respects, those of the EERI missions, but an additional aim of EEFIT missions has been to carry out building-by-building damage surveys in a number of different locations . An important aspect of EEFIT's mission is in the training of younger engineers and scientists, and this has been achieved by the participation of over 100 engineers and scientists in EEFIT missions, more or less equally divided between industry and academia. EEFIT members have been involved in the development of Eurocode 8 [32], now governing the design of structures in most EU countries and influential in the codes of many other countries, helping to bring field observations into new code provisions.

EEFIT reports have not generally set out to include general recommendations to the government (or engineering professions) of the countries visited regarding either design codes or reconstruction, though recommendations for further research are often made. But the short field mission investigations have often been the trigger for more substantial research programmes, and these are noted by EEFIT as one of the most important means by which the learnings from these missions are disseminated [4]. They have included topics such as repair and strengthening of historic structures, the development of vulnerability relationships for different structural classes, soil amplification effects (in the 1985 Mexico earthquake), liquefaction, and the vulnerability of earth dams. These research programmes have in their turn, affected both engineering practice and design regulations in the country affected and elsewhere. Of equal importance has been the establishment of lasting collaborations with colleagues and research teams in the affected countries.

2.4 Other field mission teams

This discussion has concentrated on the UNESCO, EERI and EEFIT missions primarily because these were deliberately set up to be international in scope, and also because these are the best documented archives of earthquake damage descriptions available. But post-earthquake reconnaissance missions and associated reports on damage have been made by many other organisations and by individual efforts; there are national teams in many countries set up to undertake post-earthquake reconnaissance, notably in Japan, France, Germany, Italy, Greece, Turkey and China. Many university groups have fielded reconnaissance missions to study particular aspects of earthquakes; consultancy, insurance and modelling companies have fielded their own reconnaissance missions to obtain data for their own purposes, some of which has been published; and the literature can yield many thousands of individual observations of earthquake damage, which can be of great value, particularly eyewitness accounts. Activities of a few of the other organised field investigation teams, the Japanese Society for Civil Engineering, Association Francaise du Genie Parasismique (AFPS), and the German Task Force, are presented by Spence [10].

3. Some impacts of field missions on seismic safety

The importance of the observations of field missions consists not only in their occurrence and reporting in one earthquake, but in the repetition of the same observation in many earthquakes in different regions with differing patterns of ground motion, in building stocks designed to different codes and built according to differing local practices. In the following sections the contributions which field mission observations have made in particular areas of seismic risk, understanding and mitigation are summarised.

3.1 Development and spread of earthquake design codes

Perhaps the most obvious, and most important, contribution to seismic safety has come through the development of codes of practice for the design of new structures. As Degenkolb [2] puts it: “ As far as earthquake design is concerned, by far the most important advances have been as a result of observing earthquakes”. In field investigations from the earliest days it has consistently been found that well-designed, well detailed and well-constructed buildings resist earthquake-induced forces without excessive damage, though designing to code does not necessarily protect against severe damage; damage and collapse of buildings can often be attributed to poor construction practice and lack of quality control. It has also been found that detailing for ductility and redundancy provide safety against collapse; and that a complete load path designed for seismic forces must be provided. The stiffness of the lateral load resisting system has been found to have a major effect on both structural and non-structural damage; and properly designed horizontal diaphragms are essential. Irregularities in both plan and elevation have been found to have a very significant effect on earthquake performance, especially soft stories. It has been found that inadequate distance between buildings can result in pounding damage; and stiff elements not considered in the design can strongly affect the seismic response of a building.

The relative performance of structures with different load-resisting systems has shown that unreinforced masonry buildings have performed poorly, though better if strengthened with steel ties; by contrast reinforced and confined masonry buildings have performed well. Steel frame buildings have generally performed well, though investigations following the 1994 Northridge and 1995 Kobe earthquakes found unexpected levels of damage to welded connections. Performance of precast and pre-stressed concrete buildings depend critically on the connection of the elements; exterior panels and parapets need strong anchoring to protect life safety. Though timber frame structures often perform comparatively well, various recent forms of wood frame construction have been found to have serious weaknesses. Reinforced concrete frame buildings often demonstrate similar weaknesses, including the roles of a soft storey, non-ductile elements, and irregularities in contributing to damage or collapse.

These and other observations derived from field studies have led, often through subsequent research programmes, to the progressive development of the building codes for earthquake-resistant construction in the USA, from ATC3-06 [11] through to the current version of the International Building Code [12] , and also to the development of European and Japanese codes. The US and European codes, in turn, have influenced earthquake construction codes in other countries of the world. Field mission experience has also led to the definition of a small number of Model Building Types [13, 14] used in loss estimation studies, and to the development of standards for the evaluation of existing buildings to assess whether they should be strengthened [15]. Field investigations have also helped gain acceptance for new technologies such as seismic isolation and semi-active control

3.2 Study of vernacular housing and historical structures

From the UNESCO missions onwards, field reconnaissance missions have frequently found that a large proportion of the damage has been suffered by so-called “non-engineered” structures, mostly ordinary domestic buildings built according to the local vernacular, but also larger public buildings, churches, mosques etc which may be of historical importance. Sections discussing the performance of non-engineered or vernacular structures often form a part of the field reconnaissance reports, especially those of UNESCO and EEFIT, both of which organisations specifically set out to record such damage. And in some more recent events, the 1997 Umbria-Marche and 2010 Maule earthquakes, it was possible to observe the performance of buildings which had been strengthened by relatively recent interventions specifically to improve their earthquake resistance .

Such field investigations reveal much of interest about the comparative performance of different forms of traditional construction, and also about the performance of traditional structures by comparison with more recent engineered ones. In a variety of field reports, it has been observed that lightweight structures, using timber frames, have had a surprisingly good performance. Local traditions such as *quincha* and *bahareque* in Central and South America, *himis* and *baghdadi* in Turkey, and also masonry-infilled timber frame construction *dhajji diwari* in Kashmir performed comparatively well [5]. In Pakistan, as noted earlier, the UNESCO mission following the 1974 Pattan earthquake observed much better performance in stone masonry buildings in which the flat roof was independently supported on timber columns than in those buildings in which the roof was directly supported by the walls [16]. However, conversely, many local traditional building types, especially those using field stone masonry or earthen construction, performed very poorly, and uniformly collapsed at relatively low levels of ground motion. Buildings with heavy mud roofs, or vaulted roofs, have been found to perform very poorly eg in the Bam earthquake [17]. But also certain forms of timber-frame structure, such as the traditional heavy-roof construction in Kobe, often performed badly [18].

For historical structures, several field studies have concentrated on identifying the particular mechanisms of damage using methods proposed by Lagomarsino [19] and themselves derived from field observations. Common mechanisms of damage found in the 1997 Umbria-Marche, 2009 L’Aquila and 2010 Maule earthquakes include shear cracks in walls, separation of walls at corners, overturning of facades, collapse of masonry arches and vaults, and separation of roof trusses from supporting walls. Strengthening interventions intended to improve performance seem in some cases to have contributed to the failure, as for example in the case of the Basilica of S Francesco at Assisi in 1997 [20] or more recent evidence of failure of several churches in L’Aquila, Italy [21] and Maule, Chile [22] .

What are the benefits of such studies for seismic safety? One benefit is in loss modelling: the accumulation of data on damage facilitates modelling the performance of these building types, some of which continue to be built in large numbers, and to estimate, for future events, what damage and attendant casualties will occur at an urban or regional scale given any particular ground motion scenario, leading to the development of programmes for retrofitting.. A second benefit is that the observation of relative damage enables good practice to be identified. A number of “building for safety” programmes have been set up, in recent years [23, 24] which have had the aim of bringing good earthquake resistant design practice to the construction of small buildings in rural areas through builder training, for example in the application of timber or reinforced concrete ring-beams to masonry structures, improving masonry bonding, promoting improved *quincha* construction etc, and nowadays using grouting or reinforced masonry [25]. There have been to date still relatively few such programmes and most have been confined to areas which are in the process of reconstruction following an earthquake; but they will be important as long as housing in earthquake risk areas continues to be owner-built rather than engineered. It is the systematic observations of damage from field investigations which has enabled these building for safety programmes to be developed.

A further benefit is in the application to the protection of historical monuments. In countries such as Italy and India, protection of the national heritage of historical monuments has a high priority, and a huge number of valuable monuments are at risk from earthquakes and other hazards. The observation of damage from past earthquakes has enabled a number of common mechanisms of damage to be classified [19, 27]; and this enabled not only modelling of expected damage from future earthquakes, but also has led to development of retrofit techniques for improving the earthquake-resistance of such structures with minimal impact on the integrity of the ancient fabric of the monument. Such work has been the core of two recently completed EU-funded research programmes [28]. Thus earthquake field reconnaissance missions have fed directly and indirectly into important work in the protection of historic monuments.

3.3 Recording and archiving damage data

A number of the post-earthquake field missions considered have acquired damage data in a statistical form, either from field surveys or compiled from local reports. This has indeed been a main aim of several EEFIT missions. In the past, the data were made available through the mission-specific publication reports and through the research articles that discuss the observed vulnerability of selected building classes or cross-event summaries [29]. However with the advent of new tools that allow the creation and design of web-accessible data architecture, a much wider accessibility of the data is now possible. Moreover, the publication in 2009 of the USGS ShakeMap archive (http://earthquake.usgs.gov/shakemap), provides an estimate of the ground shaking at any location in any past event. This now enables cross-event analyses against a consistent set of estimated ground motions and their variable impacts. The Cambridge Earthquake Impacts Database (CEQID) [30] and the Gem Earthquake Consequences Database (http://www.globalquakemodel.org/what/physical-integrated-risk/consequences-database/) have been designed and assembled to take advantage of these new tools. CEQID (www.ceqid.org) is based on earthquake damage data assembled since the 1960s, complemented by other more recently published and some unpublished data. The database assembles the data into a single, organised, expandable and web-accessible format, with a direct access to event-specific shaking hazard maps. Analytical tools are available which enable cross-event relationships between casualty rates, building classes and ground motion parameters to be determined. The Database is freely accessible to all users, and uses a simple xml format suitable for data mining. Location maps and images of damage are provided for each earthquake event. The Database links to the USGS ShakeMap archive to add data on local intensities and on measured ground shaking.

Currently the CEQID database contains data on the performance of more than 1.3 million individual buildings, in over 600 surveys following 51 separate earthquakes, and the total is continuously increasing. The database also has a casualty element, which gives total recorded casualties (deaths, seriously and moderately injured), and casualty rates as a proportion of population with definitions of injury levels used, and information on dominant types of injury, age groups affected etc. Of the 51 events currently in the database, 23 were in Asia and the Pacific (12 of which were in Japan), 17 in Europe, Turkey and North Africa, and 11 in North or South America. Most of the surveys have been done in events since 1990; among these 51 events, 18 were prior to 1990, 21 between 1990 and 2000, and 14 since 2000. Of the 1.3 million buildings in the database, 0.45 million do not have a well-defined building or structural typology given; of the remainder, 78% are of timber frame, 14% masonry, 5% reinforced concrete, and 3% are of other structural types.

The cross event analysis tools of CEQID and GEMECD allow the construction of charts of empirical damage data related to consistent measures of ground motion derived from the USGS Shakemap archive to be used to show the relationship between damage and any chosen measure of ground motion. Thus post-earthquake damage data can be used directly to enable empirical fragility relationships to be developed for any given building type, making an important contribution to loss modelling capability.

EEPImap (www.snapandmap.org) is a searchable archive of more than 12,000 photographs of post earthquake damage each geolocated, and each with an assessment of structure type, and level of damage defined using EMS-98 definitions. Such databases, continuously expanded and globally accessible, make a very important contribution to seismic safety through their contribution to loss modelling, an essential step in any programme to devote funds (public or private) to reducing seismic risk.

3.4 Observing reconstruction processes

A post earthquake field mission provides just a snapshot in time of a process of emergency management and recovery which can take years. Most post-earthquake field missions have been concerned with recording damage and consist predominantly of engineers. For this purpose, a visit within at most a few weeks is needed. But learning lessons about recovery processes can be of equal importance to the international community, and in recent years there has been an increase in the number of studies of this aspect. Some of these have involved repeat missions by reconnaissance teams, or by individual members of reconnaissance teams, some months or even years later, when the recovery process can be observed and analysed. Both EERI and EEFIT have organised such repeat missions, and international comparisons have been attempted by Comerio [31] and Platt and So [26].

For housing recovery, Comerio [31] has developed an international comparison metric based on two parameters seen as key to recovery, the degree of government involvement in the reconstruction process, and the extent of individual citizen participation. Using the authors judgement, the housing recovery process of each of nine countries after different disasters has been plotted on a chart Figure 2.

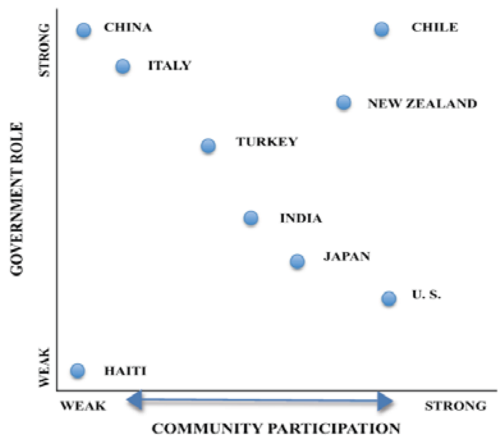

Figure 2 International comparisons of post-disaster housing recovery experiences [31]

The chart indicates a wide variety of different approaches: Chile and New Zealand have combined both "top-down" and "bottom-up" approaches, providing government leadership and funding along with community empowerment in decision-making. By contrast, China and Italy took strong government leadership roles in providing replacement housing but did not engage local communities in most aspects of the decision making. USA and Japan provide strong leadership during the emergency phase and fund some aspects of recovery such as infrastructure and public facilities, but leave most of the housing reconstruction to the private market.

Platt and So [26] in a review of recovery following 10 disasters worldwide also argue the need for a balance between speed and deliberation to achieve the best outcome as in Chile, and suggest that in countries facing known major hazards, recovery would be speedier and more effective if key decisions were made in advance, on general matters such as assigning responsibilities, regional delegation of powers, and degree of citizen involvement.

Given the huge variety of systems of national and local government, levels of economic development, and social structures in earthquake affected countries, no one approach can be recommended for all cases, but the assembly recording and comparison of international experiences can provide useful exemplars to assist countries in developing the most appropriate recovery process in a given situation.

4. Implications for future field missions

Over the last 30 years there has been a huge change in the technology available to support earthquake field missions. Digital photography, GPS positioning, the internet, mobile phone networks, high resolution satellite reconnaissance, social media have all arrived and made their mark on the way earthquake reconnaissance missions are conducted. Technology will continue to evolve at a rapid pace in both predictable and unpredicted ways, allowing improvements in speed of operation, in communication between team members and base, and in the capturing of detail: through photographic communication, some people will be able to contribute to the work of field missions without travelling to the affected area. These technological developments, in turn, will enable field mission teams to be more international and facilitate an increase in local participation.

The development of higher-resolution and other forms of remote sensing tools for damage assessment is not likely to eliminate the need for investigators in the field to view damage from close range. But it will enable teams to organise their field operations with support from continuously updated and pre-analysed remote sensing images. The development of databases of the building stock inventory (already in development in many areas) will enable teams to have access to pre-event data and images of each damaged object. As a response to such changes field teams may in future be smaller, more focussed on special aspects and deployed at different times.

The collection of building-by-building data on damage has been an important feature of the work of some reconnaissance missions, and it is largely through such damage surveys that empirical fragility relationships for loss estimation have been developed. It is often assumed by reconnaissance teams that detailed building damage surveying will be done, over time, by national authorities and made available. But such official damage data often turns out to be inadequate for use in loss estimation, with damage levels and construction typologies poorly defined, and undamaged buildings often omitted. Assembling damage data through well-chosen local building-by-building sample datasets will continue to be of vital importance, and field surveys can now be supported through remote sensing to locate appropriate samples across a range of areas, not just those most heavily damaged. This will enable existing fragility estimates for national building stocks to be updated as new damage data becomes available.

There is still a need to improve the level of international collaboration between field mission teams. The sites of a number of the most important earthquakes in recent years have been visited by multiple teams, which usually work independently of each other [10]. In many of the affected countries significant expertise in earthquake engineering now exists, and it is vital for visiting reconnaissance teams to work with local experts, to learn from them, and share their own knowledge. This already happens, but needs to be given priority to ensure reconnaissance missions contribute most effectively to improving seismic safety.

Future post-earthquake field missions are likely to be as much concerned with helping with developing resilience as recording damage: this will give rise to a need for a series of missions at different stages of the recovery cycle, and for the involvement of more expertise from complementary disciplines such as sociology and urban planning. The monitoring and evaluation of the recovery process can in future become a central part of the role of reconnaissance missions.

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6. References

[1] Ambraseys NN (1988): Engineering Seismology, *Earthquake Engineering and Structural Dynamics*, 17, 1-105

[2] Degenkolb H (1994): *Connections: the Oral History Series*, conducted by Stanley Scott, Earthquake Engineering Research Institute, Oakland, California.

[3] EERI (2004): *Learning from earthquakes: The EERI Learning from Earthquakes Program: A brief Synopsis of Major Contributions*, www.eeri.org. (accessed 6.1.2014)

[4] Booth E, Wilkinson S, Spence R, Free M and Rossetto T (2011): EEFIT: the UK Earthquake Engineering Field Investigation Team, *Forensic Engineering* 164 3, pp 117-121

[5] Spence R (2007): Saving lives in earthquakes: successes and failures in seismic protection since 1960, *Bulletin of Earthquake Engineering*, 5: 139-251

[6] Fournier-D'Albe EM (1986): Foreword, in Ambraseys NN, Moinfar AA and Tchalenko JS (eds) *UNESCO Earthquake Reconnaissance Mission Reports 1963–1981*.UNESCO, Paris.

[7] EERI (1986): *Reducing earthquake hazards: Lessons learned from earthquakes*, Publication 86-02, EERI Oakland California.

[8] EERI (1995): *Post earthquake Investigation Field Guide*. www.eeri.org

[9] Ambraseys NN (1976): Field Studies of Earthquakes, Discussion Paper for *Intergovernmental Conference on the Assessment and Mitigation of Earthquake Risk*, UNESCO, Paris.

[10] Spence R (2014): The full-scale laboratory: the practice of post-earthquake reconnaissance missions and their contribution to earthquake engineering (The Third Nicholas Ambraseys Lecture), Chapter 1 in Ansal A (ed) *Perspectives on European Earthquake Engineering and Seismology*, DOI 10.1007/978-3-319-07118-3_1, Springer.

[11] ATC (1978): *Amended Tentative Provisions for the Development of Seismic Regulations for Buildings ATC-3-06*, Applied Technology Council, California, http://www.atcouncil.org/pdfs/atc306.pdf

[12] International Code Council (2012) : *2012 International Building Code*, International Code Council,

[13] FEMA (2003**):** *Hazus Technical Manual*. Federal Emergency Management Agency, Washington, DC.

[14] Jaiswal KS, Wald DJ, Earle PS, Porter K and Hearne M (2011): Earthquake Casualty Models in the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) System, Chapter 6 in in Spence R, So E and Scawthorn C (eds), *Human Casualties in Earthquakes: Progress in Modelling and Mitigation*, Springer.

[15] ASCE (2003): *Seismic Evaluation of Existing Buildings (ASCE/SEI 31-03)* , American Society of Civil Engineers

[16] Ambraseys NN, Lensen G, and Moinfar A (1975): Pakistan:The Pattan Earthquake of 28 Decemeber 1974, Serial no FMR/SC/GEO/75/134, UNESCO, Paris.

[17] Maheri M R, Naeim F and Mehrain M (2005): Performance of adobe residential buildings in the 2003 Bam, Iran, Earthquake, *Earthquake Spectra*, Special Issue 1, Vol 21 pp S337-S344

[18] Chandler A and Pomonis A (editors) (1995): The *Hyogo-ken Nanbu (Kobe) Earthquake of 17 January 1995: A Field report by EEFIT*, Institution of Structural Engineers, London.

[19] Lagomarsino S, Brencich A, Bussolino F, Moretti A, Pagnini LC and Podesth S **(**1997) :Una nuova metodologia per il rilievo del danno alle chiese: prime considerazioni sui meccanismi attivati dal sisma, *Ingegneria Sismica* Vol 14, No 3**,** Sept-Dec 1997,70-82.

[20] Spence R (editor) (1998): *The Umbria March Earthquakes of 26 September 1997: a Field Report by EEFIT*, Institution of Structural Engineers, London.

[21] Cimellaro GP, Reinhorn AM, De Stefano A (2011): Introspection on improper seismic retrofit of Basilica Santa Maria di Collemaggio after 2009 Italian earthquake. *Earthq Eng & Eng Vib* 10: 153-161, DOI: 10.1007/s11803-011-0054-4

[22] D'Ayala D and Benzoni G (2012): Historic and Traditional Structures during the 2010 Chile Earthquake: Observations, Codes, and Conservation Strategies, *Earthquake Spectra*, 28(S1), 425-451. doi:10.1193/1.4000030

[23] ASAG (1996): *ASAG's Intervention through Technology Upgrading for Seismic Safety*, Ahmedabad Study and Action Group, Ahmedabad, India.

[24] Schilderman, T (2004): Adapting traditional shelter for disaster mitigation and reconstruction: experiences with community-based approaches, *Building Research and Information*, 32(5), pp 414-426

[25] NSET (2005): *Earthquake Resistant Construction of Buildings, Curriculum for Mason Training*, NSET, http://www.nset.org.np

[26] Platt, S and So, E (2016): Speed or deliberation – a comparison of post-disaster recovery in Japan, Turkey or Chile , *Disasters Journal*, DISA-Oct-14-1602.R1 (in press)

[27] D'Ayala, D. (2013). Assessing the seismic vulnerability of masonry buildings. *Handbook of Seismic Risk analysis and management of civil infrastructure systems* (pp. 334-365). Woodhead publishing.

[28] D'Ayala DF and Paganoni S (2011): Assessment and analysis of damage in L'Aquila historic city centre after 6th April 2009 earthquake, *Bulletin of Earthquake Engineering*, 9(1), 81-104. doi:10.1007/s10518-010-9224-4.

[29] Coburn A and Spence R (2002): *Earthquake Protection*, John Wiley.

[30] Spence R, So E, Jenkins S, Coburn A, and Ruffle S (2011): A Global Earthquake Building Damage and Casualty Database, Chapter 5 in in Spence, R, So, E and Scawthorn, C (eds), *Human Casualties in Earthquakes: Progress in Modelling and Mitigation*, Springer.

[31] Comerio M (2013): *Housing Recovery in Chile: a Qualitative Mid-Program Review*, Department of Architecture, University of California, PEER Report 2013/01

[32] CEN (2005): *European Standard EN 1998-1: Eurocode 8: Design of structures for earthquake resistance. Buildings*, European Committee for Standardization, Brussels, Belgium.