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In this issue

EEFIT Special Issue

Editorial Introduction

Last year was a rather busy year for the Earthquake Engineering Field Investigation Team (EEFIT), which deployed field missions following damaging earthquakes in Japan, Ecuador and central Italy. Most readers of this newsletter will be familiar with EEFIT's activities over more than three decades. Booth et al.'s article in Vol. 23, No. 2 (November 2011) of this newsletter summarised the organisation's founding objectives:

> *EEFIT's founding objectives, essentially unaltered today, stated that its purpose was to enable British earthquake engineers, architects and scientists to collaborate with colleagues in earthquake prone countries in the task of improving the seismic resistance of both traditional and engineered structures. Training of engineers through observing how full scale structures actually responded to ground motions was subsequently added as a key objective. These goals were to be achieved principally by conducting field investigations following major damaging earthquakes and reporting to the local and international engineering community on the performance of ordinary civil engineering and building structures under seismic loading.*

For this issue of the SECED newsletter, I asked EEFIT teams from 2016 to provide short summary articles about their mission findings. As is customary, the participants in those missions have more fully documented their findings in reports, journal and conference papers, and presentations at the Institution of Structural Engineers. Interested readers can follow up on references to this work in the papers contained herein.

Noting Edmund Booth's key involvement in the founding of EEFIT, it is timely to remind readers about his upcoming 16th Mallet–Milne lecture, entitled 'Dealing with Earthquakes'. It will be held at the Institution of Civil Engineers in London on 24 May 2017. Edmund provided a progress report on the research he is conducting for the lecture in Vol. 27 No. 2 of this newsletter in August last year.

For more information about the Mallet–Milne lecture and other upcoming SECED events, please visit the website: www.seced.org.uk.

The April 2016 Kumamoto Earthquakes, Kyushu, Japan

G. Campbell, K. Goda, L. Hulme, B. Ismael, L. Ke, R. Marsh, P. Sammonds, E. So
EEFIT-Kumamoto Team

Two large-magnitude earthquakes occurred on 14 and 16 April 2016 in central Kyushu Island, southern Japan (Figure 1). Sudden right-lateral motion of up to two metres on the Hinagu and Futagawa faults generated the Mw 6.1 foreshock and Mw 7.1 mainshock, respectively (Figure 2). The primary effect of the earthquake ground shaking and the secondary landslides, which were triggered by the earthquakes, in combination with the double shock impact, caused significant and widespread damage and disruption to the urban and rural regions of Kumamoto and Aso respectively. The measured ground motions exceeded the code design values by a factor of up to 3, as shown in Figure 3.

In total, 69 people died (49 deaths were directly caused by building collapses and landslides and 20 deaths were from indirect causes), while the total number of casualties was 1,747. Approximately 8,050 houses were destroyed and more than 180,000 people were evacuated immediately after the Mw 7.1 mainshock. The total economic loss was estimated to be 24 to 46 billion US dollars (Cabinet Office of Government of Japan, 2016).

To learn key lessons from the observed damage and impact caused by the Kumamoto earthquakes, an Earthquake Engineering Field Investigation Team (EEFIT) mission was organised and deployed. The EEFIT-Kumamoto team comprised international members from academia and industry with broad and varied expertise including engineering seismology and earthquake ground motions; geotechnical, civil, and structural engineering; geophysics, earthquake geology and surface rupture; and earthquake impact and recovery. In addition, scientific support was provided in the field from colleagues of Kyoto and Gifu Universities in Japan.

The field mission lasted 5 days from 22 to 26 May 2016. The main rural areas, towns and cities surveyed for structural damage, geotechnical failures, and fault rupture included (from west to east): Kumamoto Port, Uto City, Kumamoto City (Centre), Mashiki Town, Nishihara Village, Aso City and Minami Aso Village. Both the city centre of Kumamoto and Mashiki Town are located in very

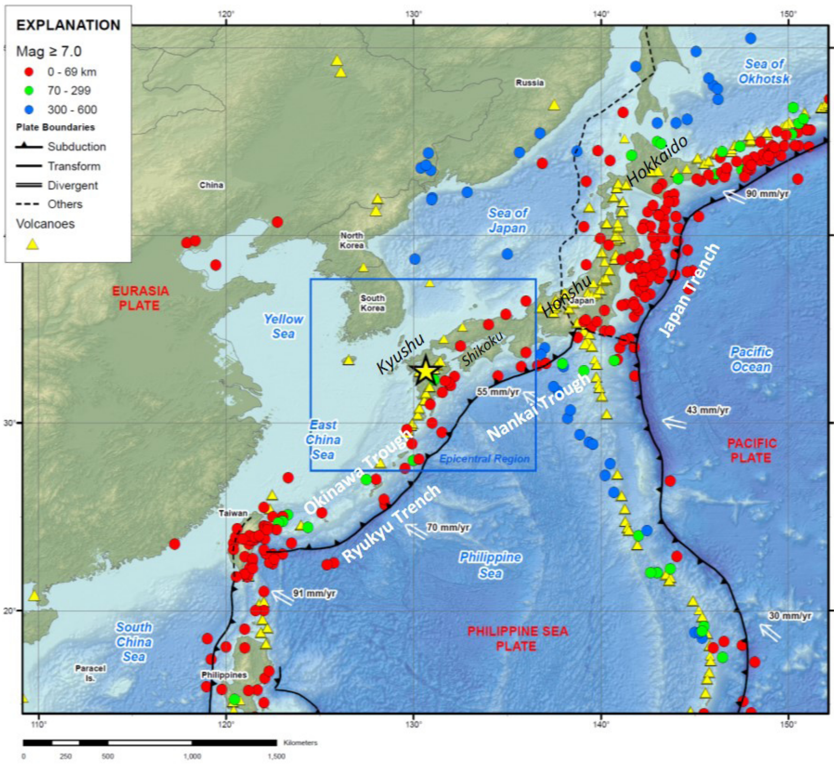

Figure 1: Regional tectonic setting of Japan showing the epicentre of the Kumamoto magnitude Mw 7.1 mainshock earthquake (yellow star).

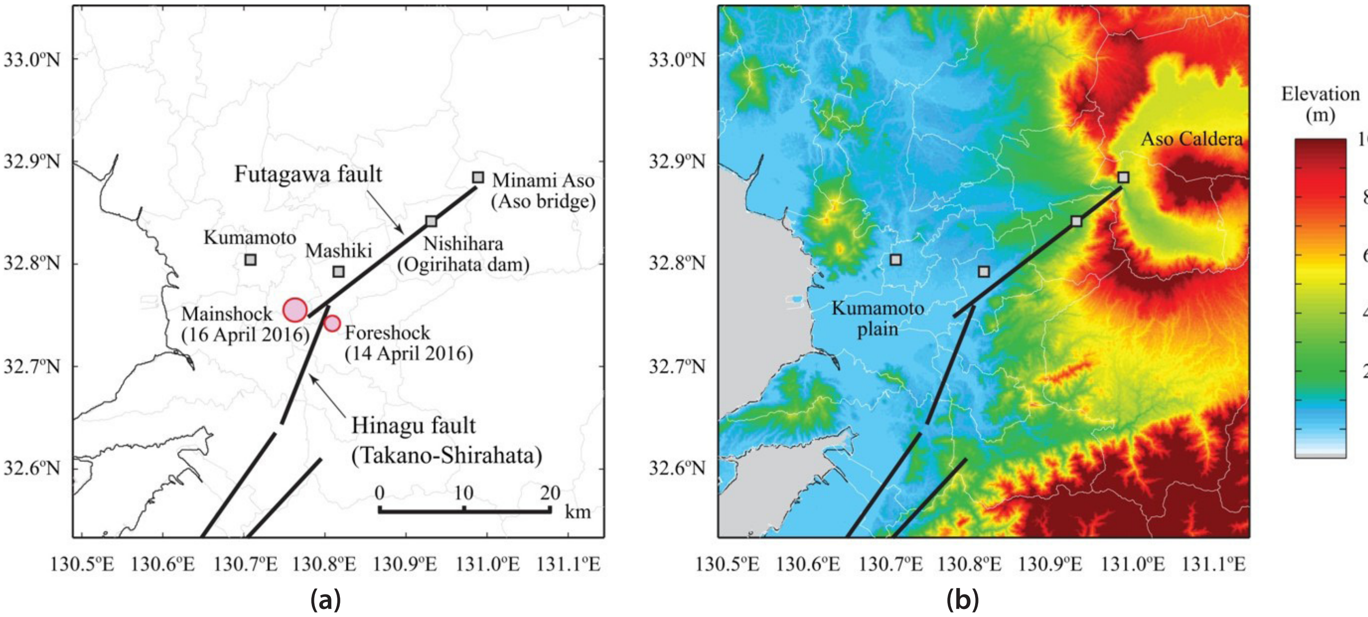

Figure 2: (a) Foreshock and mainshock Kumamoto earthquake epicentral locations on the Hinagu and Futagawa fault, respectively; (b) Topography map of the study region showing the low-lying Kumamoto alluvial plains in the west relative to the high topographic relief of the Aso volcanic caldera (crater) in the east.

close proximity to the two earthquake faults (Figure 2).

In general, damage survey data and observations indicated that the majority of the collapsed buildings were timber houses with heavy roof tiles, which were constructed according to the pre-1981 seismic design provisions (Nakashima and Chusilp, 2003; Figure 4). Typically, reinforced concrete (RC) buildings performed better than older steel and timber buildings (Figures 4, 5 and 6). The moderate and heavy damage to RC buildings was in the form of shear cracking to RC shear walls and joint damage to poorly detailed RC frames, in addition to less frequently observed partial and extreme soft-storey collapses. Several cultural heritage buildings (e.g. Kumamoto Castle and Aso Shrine) were also badly damaged due to the earthquakes.

In terms of geotechnical failures, many significant bridges, embankments, retaining walls, tunnels and a dam were damaged by slope failures, lateral spreading, settlement, and landslides mostly in the high-relief region of Aso (Figures 2b and 7). This is where the Futagawa fault intersects with the west wall of the Aso volcanic caldera. Liquefaction effects were observed, in the form of ejected sand at Kumamoto Port (which is an artificial island), and in the form of settlement, lateral spread, and uplifted drain covers along the roads that cross the alluvial plains close to

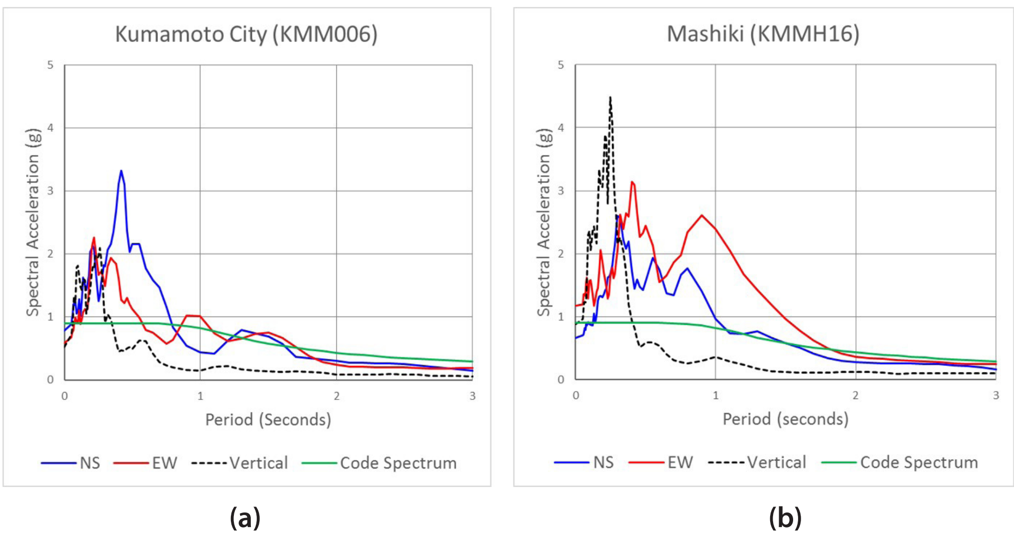

Figure 3: Measured ground accelerations compared to the code spectrum in (a) Kumamoto City Centre, and (b) Mashiki Town.

(a) (b)

Figure 4: Damage to timber frame houses, (a) complete collapse of pre-1981 structure, and (b) an example of storey collapse.

Mashiki Town.

The mainshock earthquake generated two types of surface rupture (Figure 8): 1) right-lateral offsets related to strike-slip motion, and, 2) vertical offsets associated with extensional motion. The team made field measurements of the amount and type of offsets, in addition to carrying out an aerial-photo survey of a 300 m section of the surface strike-slip rupture using a drone. The aerial photos have been used to generate a high-resolution digital model of the surface rupture orientation and geometry. High resolution field and remote-sensing measurements such as this are important as they help us understand the scaling relationship between the fault surface offset and the earthquake moment magnitude.

In terms of relief and recovery, interviews with official and voluntary emergency response personnel in addition to evacuees indicated that the rate of recovery and the ability to 'build back better' may be dependent on the approach employed by the different municipalities affected by the earthquakes. A day after the mainshock, there were 855 shelters and 183,883 evacuees recorded. The various evacuation centres typically housed three types of people: people with partially collapsed or completely collapsed houses; people living in residential blocks with disrupted services, and those who were too scared to return home. The affected municipal governments provided gymnasiums, schools and other public buildings for use as public shelters (Figure 9).

(a) (b)

Figure 5: Damage to RC frame buildings; (a) soft-storey collapse of an apartment building (Tajiri et al., 2016), (b) west façade of the Uto City Office.

(a) (b)

Figure 6: Steel building failures Mashiki Town: (a) bottom-storey drift; (b) four-storey collapse.

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(a) (b)

Figure 7: (a) Landsliding in the high-relief Aso Caldera region at the east extent of the main Futagawa fault; (b) the major Aso landslide that blocked the main road route between Kumamoto City and the rest of east Kyushu Island.

SECED Newsletter

The SECED Newsletter is published quarterly. All contributions of relevance to the members of the Society are welcome. Manuscripts should be sent by email. Diagrams, pictures and text should be attached in separate electronic files. Hand-drawn diagrams should be scanned in high resolution so as to be suitable for digital reproduction. Photographs should likewise be submitted in high resolution. Colour images are welcome.

Please contact the Editor of the Newsletter, Damian Grant, for further details: damian.grant@arup.com.

(a)
(b)

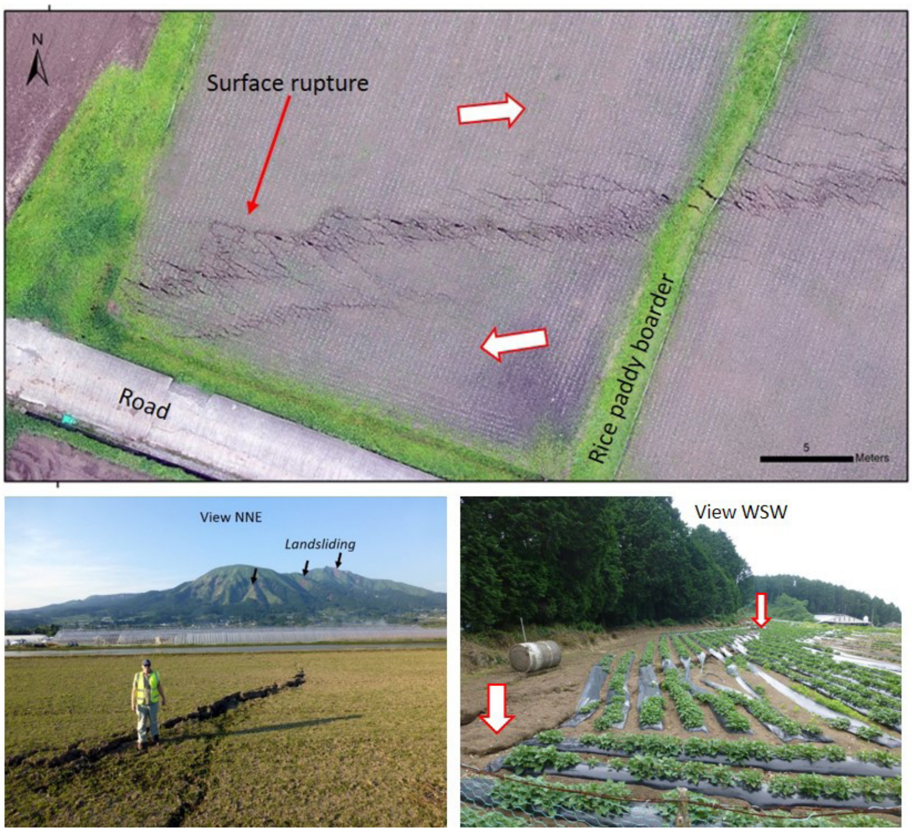

Figure 8: (a) Aerial photo of the earthquake surface rupture right-laterally displacing (by ~2 m) rice paddy fields east of Mashiki Town, taken by the EEFIT drone; (b) examples of the surface rupture (~1.5 m) vertical offsets.

Figure 9: Various evacuation centre temporary settlements erected after the Kumamoto earthquakes.

The 16 April 2016 Musine, Ecuador Earthquake

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EEFIT-Ecuador Team

On 16 April 2016 an Mw 7.8 earthquake with epicenter 29 km south-southeast of Muisne caused severe damage to towns along the Pacific coast of Ecuador. The tourist centres of Pedernales, Bahía de Caráquez, Canoa and Manta were heavily affected. The event killed a total of 663 people (12 missing), injured about 5,000 and an estimated 80,000 people were displaced. The estimated costs of reconstruction totaled $3.3bn.

Ecuador has a history of large seismic events exceeding Mw 7. The epicentre of the 2016 earthquake was located at the southern end of the 400–500km long rupture area of the 1906 Mw 8.8 event which generated a tsunami that killed hundreds of people (USGS, 2016). Closer to the 2016 epicentre, a Mw 7.8 earthquake occurred in 1942, 43km south of the recent April event, and a Mw 7.2 event occurred in 1998 close to Bahía de Caráquez.

The Earthquake Engineering Field Investigation Team (EEFIT) deployed to the region between 24 May–7 June with the objective of recording observations and measurements that would help the scientific and professional community understand the event and its consequences. The multi-disciplinary team comprised both structural and geotechnical engineers, and social scientists, in order to gain a full range of perspectives of the impacts of the event. Impacts were widespread, with damage along the coast extending from Esmeraldes in the north, to Guayaquil in the south, a distance of around 400 km. The team surveyed the following towns: Manta, Portoviejo, Bahía de Caráquez, Canoa, Jama, Pedernales, and Chamanga.

The team collected damage data using both rapid methodologies (gathering information on construction type, EMS-98 damage grade, and number of storeys), and more detailed techniques including Arup's REDi framework (Almufti and Willford, 2013), and an extension to GEM's inventory data capture tool (Brzev et al., 2103). In total, over 1300 buildings were surveyed: the majority of buildings were reinforced concrete light frame buildings with masonry infill (~72%), and the rest were formed of timber frame with masonry infill, bahareque/quincha, bamboo and a handful of industrial steel and unreinforced masonry structures.

Lack of fundamental engineering design for lateral loads, including inadequate detailing, poor materials, irregularities, and seismic weaknesses such as short columns (see Figure 1), were observed as the primary causes of structural damage. Non-structural damage to the masonry infill walls was heavy, since many were slender and not tied into the RC frames (see Figure 2). Additionally, the lack of adequate maintenance to timber and bamboo structures induced some failures. Several instances of failures at upper levels were observed (see Figure 3), which were caused either by changes in stiffness in elevation, or potentially by poor connections between original buildings that had been extended vertically at a later date. It must be noted that demolition progressed rapidly, meaning that many of the worst damaged buildings had been removed prior to the team's arrival, and therefore surveys of these specific ones were not possible. However clear relationships were observed in the data collected, particularly between the spectral response derived from the recorded ground motions

Figure 1: Short column failure to a school in Pedernales.

Figure 2: Out-of-plane failure to slender and inadequately fixed clay brick masonry infill.

(a) (b)

Figure 3: Upper level soft storey failures; (a) in Manta, and (b) in Portoviejo.

and buildings with certain heights (and hence estimated fundamental periods (CEN, 2004)), as shown in Figure 4.

The team also surveyed a number of bridges. The base isolated Las Caras bridge which connects Bahía de Caráquez and San Vincente was found to have minimal damage, allowing it to remain operational throughout the humanitarian response. A suspension footbridge in Canoa was found to have collapsed following the failure of connections at the northern end and uplift of the anchor blocks at the southern end (see Figure 5).

For further observations from the Ecuador EEFIT team, refer to Franco et al. (2017).

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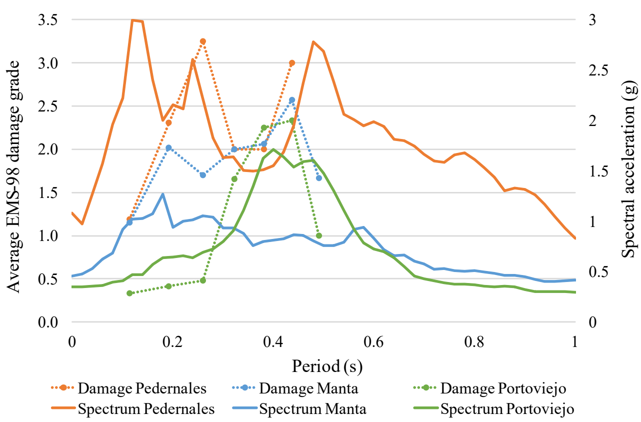

Figure 4: Relationship between response spectra from recorded ground motions and surveyed damage.

Figure 5: Collapsed footbridge in Canoa.

The August 2016 Earthquake Sequence of Central Italy

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EEFIT-Amatrice Team

At 3.36 am on 24 August 2016 a Mw 6.2 (USGS) earthquake struck the central region of Italy, with epicentre in the Apennines range, near the village of Accumoli and with a fault rupture length of 25 km. Earthquake shaking was felt as far as Rome (120 km SW), Florence (220 km NW) and Urbino (200 km N). The worst affected region has a radius of 20 km around the epicentre, including a number of towns and small villages across the regions of Umbria, Lazio and Marche.

Between the 4th and 15th of October the Earthquake Engineering Field Investigation (EEFIT) team from the United Kingdom deployed three teams in the area struck by the earthquake. The reconnaissance mission aimed at carrying out observations of rupture surface, investigating soil conditions at accelerometric stations which registered the event, documenting geotechnical failures, and collecting geo-referenced damage data for structures.

This article presents a short summary of the mission activities and findings. For further details, the readers are referred to the webinar held at the The Institution of Structural Engineers (IStructE):

https://istructe.hosted.panopto.com/Panopto/Pages/Viewer.aspx?id=2bf41c22-e589-401d-9525-9c2c996f55b1

and to the mission's blog:

https://eefitamatrice.wordpress.com/

The first part of the mission focussed on investigating surface effects, including primary surface ruptures, environmental effects and ground motion recordings.

Slip at depth on the fault plane that generated the main shock propagated to the surface and offset the hillside of Mt Vettore (~20 km north of the town of Amatrice). The offsets seen were in the range of 3–30 cm along a 5 km long section of the fault. The mission mapped part of the surface rupture, adding to observations made by colleagues from UCL, Leeds, Durham and several Italian institutions. This involved taking measurements of the throw (vertical offset), heave (horizontal offset) and slip (total offset), the orientation of the rupture and the slip direction (Figure 1). This data will be used to study the relationship between the size of the offset and the geometry of the rupture.

As well as primary surface ruptures, the earthquake also generated secondary environmental effects, including landslides, rockfalls and ground cracks. By mapping out the location of these effects and the size or volume, an intensity level (similar to the European Macroseismic Scale, EMS) can be determined. The benefit of the ESI (Environmental Seismic Intensity) scale is that it can be applied anywhere within an affected area and does not introduce a built environment bias (see Figures 2 and 3). The team travelled around the epicentral area recording these effects, focussing on the areas around the towns of Amatrice, Accumoli and Arquata del Tronto. They observed many effects around the towns of interest, mainly landslides and rockfalls with fewer ground cracks and hydrological effects. Using these

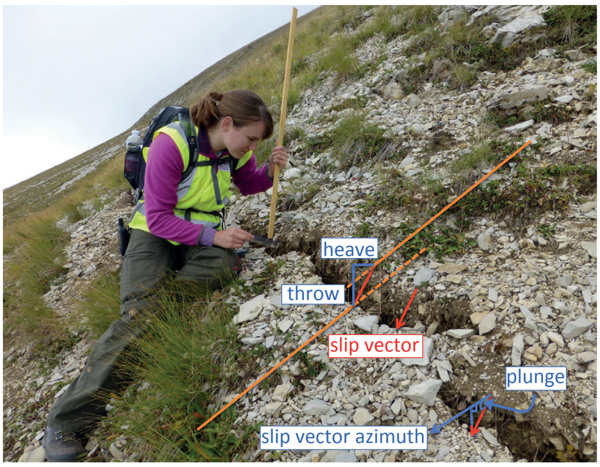

Figure 1: Explanation of measurements taken in the field.

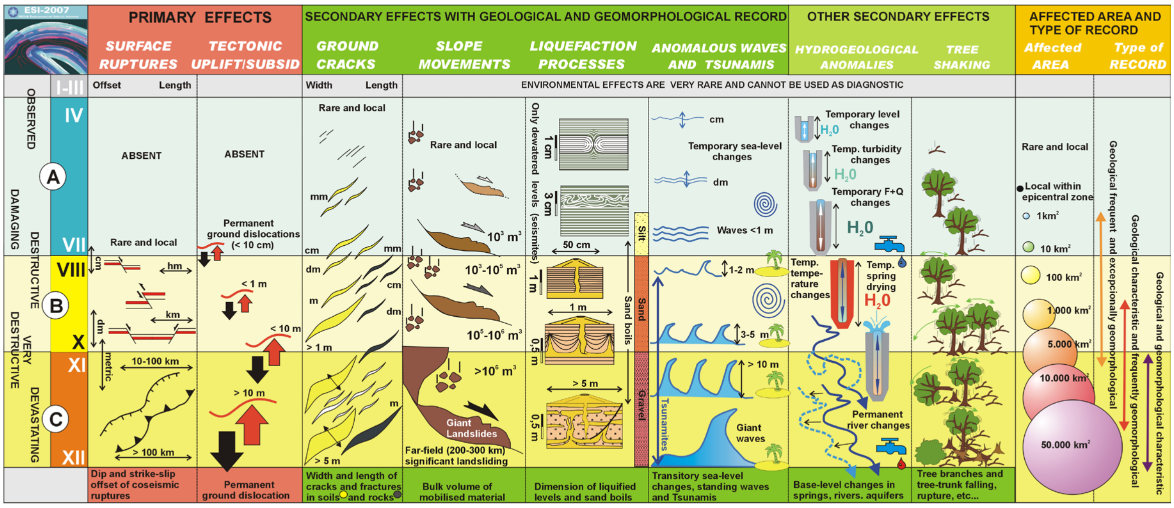

Figure 2: Environmental Seismic Intensity scale (image from https://en.wikipedia.org/wiki/Environmental_Seismic_Intensity_scale; full descriptions available at http://www.isprambiente.gov.it/en/projects/soil-and-territory/inqua-scale/environmental-seismic-intensity-scale-esi-2007a.

observations, they will determine the intensity of the shaking from environmental effects and will compare the ESI values to the intensity determined by the building assessments made by others on the mission.

Ground motion that occurred during the earthquake was recorded by numerous seismometers in the surrounding region; these stations also record the peak ground acceleration. The team visited several stations that recorded the highest levels of ground motion. On their visits, they looked specifically at the sites of the seismometers to determine whether localised site effects could explain the high ground motions observed during the earthquake.

The second part of the mission focussed on the structural engineering aspects related to the earthquake. The building stock in the urban centres affected mainly consists of historic rubble masonry structures, with a modest proportion of reinforced concrete (RC) constructions.

As might be expected, much of the damage observed was to heritage structures predominantly of masonry construction, and due to the occupancies in the areas affected much of the damage was to residential structures, with some commercial buildings in town centres. The historic centre of Amatrice, for example, was severely damaged and most of the 298 fatalities of the 24 August event occurred there. The damage level in Amatrice and certain other locations is extreme. The images shown in Figure 4 are a before and after image from approximately the same position.

The teams visited other severely damaged towns including Accumoli, Arquata del Tronto and Pescara del Tronto, as well as numerous other smaller villages. In all locations rapid damage surveys were carried out on-site and subsequently integrated through the use of 360° imagery.

Special focus was dedicated to churches in the municipality of Norcia. At the time of the mission, i.e. in the aftermath of the August earthquake, churches in the Norcia area showed reasonably satisfactory performance. Retrofitting

Figure 3: Measuring secondary environmental effects.

(a) (b)

Figure 4: Amatrice's Corso Umberto I, (a) before (from Google Street view), and (b) after the earthquake.

actions taken as a result of previous events in the area such as the 1997 earthquake were observed and discussed with local experts who joined the mission.

This latter aspect is relevant since two other destructive earthquakes on the 26th (Mw 6.0) and the 31st (Mw 6.5) of October struck the same area. The epicentres of these two events were close to Norcia municipality and located in the proximity of the churches inspected. Many of the heritage structures inspected during the mission collapsed dramatically after the subsequent earthquakes. There is evidence that some of the potential church collapse mechanisms identified during the mission were triggered by the subsequent earthquakes contributing to the structural failures; see for example Figure 5.

Special attention was also paid to the performance of critical buildings such as schools and hospitals. Notable examples are the two schools surveyed outside the ancient walls of the town of Norcia: a masonry and a RC building. While the first one was not in use and presented some damage, the RC building was functional. From the visual survey done by the team, damage to the masonry building was evaluated by the team as a damage state 3 according to the EMS-98 scale (Grüntal, 1998). The inspection on the RC building showed that even if it could be classified as a non-ductile RC dating designed before 1980, the school was subjected to a successful retrofitting intervention (probably after the 1997 Umbria earthquake) as highlighted by steel tubular braces at the first story (Figure 6).

Finally the teams surveyed a number of bridges and critical infrastructures. Masonry arched bridges are the typology that suffered the most damage during the earthquake. One example is the "Ponte a 3 Occhi" bridge, a 70 m long structure located approximately one kilometre South of Amatrice (Figure 7). In the aftermath of the 24 August

(a) (b) (c)

Figure 5: St. Eutizio Abbey: façade gable mechanism as observed during the mission, after the 26th of October Mw 6.0, and after the 30th of October Mw 6.5.

(a) (b)

Figure 6: (a) RC school building retrofitted after the 1997 earthquake; (b) closer view of retrofit.

earthquake, the bridge failure made national headlines as it was closed to traffic cutting off one of the key access routes for the emergency services. Its strategic importance was highlighted by the need for the army to construct a new by-pass road which was opened just over a week after the earthquake (Figure 7).

Masonry bridges closed to traffic suffered damage to the earth-retaining abutments suggesting that this particular structural element needs careful consideration in bridge seismic design. Masonry arches showed that they can perform their structural function even if they suffered damage, such as cracking, thanks to their inherent structural redundancy.

Damage to RC viaduct structures was found to be limited, and mainly related to pounding effects. Such damage did not affect the operability of the viaducts in the affected areas. Most of the RC viaduct types observed were not designed and detailed to resist seismic actions, however, they did not present high seismic vulnerability because of their inherent capacity. Such consideration can drastically change when imposed displacements are larger and loss of support phenomena can occur. Fortunately, the displacement demands related to the 24th of August seismic event did not cause undue inelastic deformations.

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(a) (b) (c)

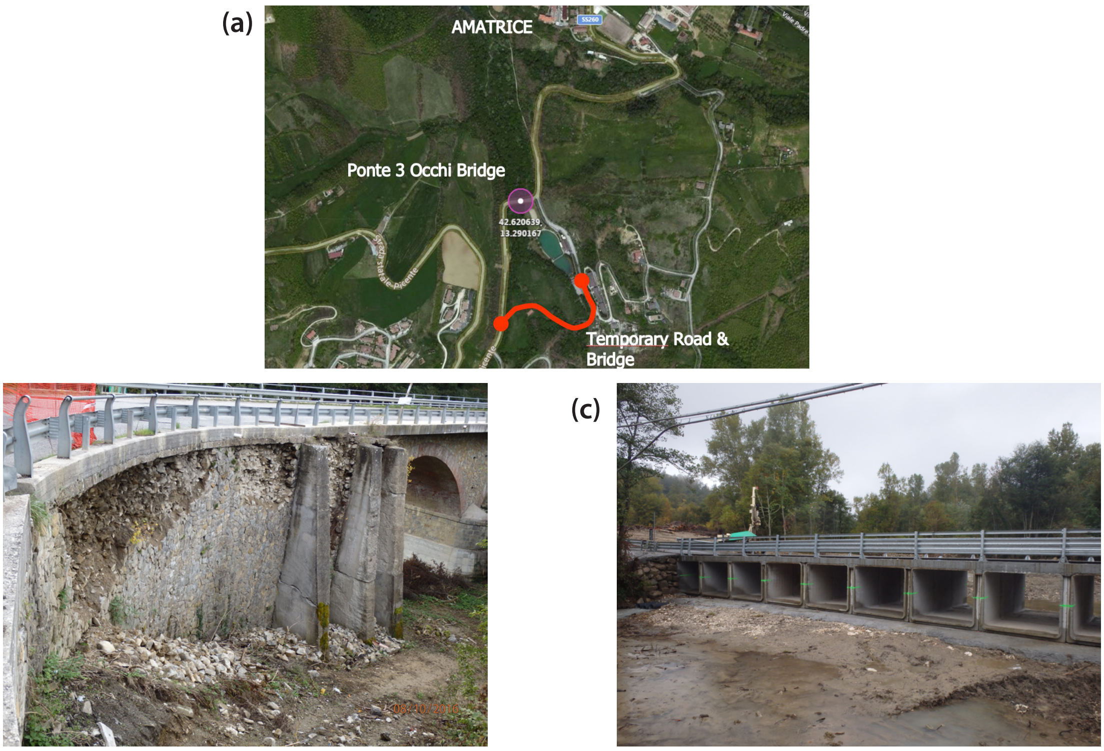

Figure 7: (a) "Ponte a 3 Occhi" bridge map, (b) damage to bridge, and (c) new by-pass road bridge.