# Investigating the cross-disciplinary components of Earthquake Early Warning Systems

Thesis submitted to University College London for the degree of Doctor of Philosophy

by

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# *Declaration*

I, Omar Alejandro Velázquez Ortíz confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

# Abstract

Earthquake early warning (EEW) systems typically provide early estimates of earthquake magnitude, hypocentre location and/or ground-shaking estimates, as well as alerts ranging from a few seconds to tens of seconds, before the arrival of the damaging ground shaking at a target site. The warnings provided by these systems allow for the implementation of fast protection actions carried out by individuals like ‘drop, cover, and hold-on’, or the evacuation of buildings if the lead time is long enough. Nevertheless, the information and warning time provided by an EEW system could also be used by earthquake engineers as EEW seems to bear a powerful potential for the automatic activation of protection measures for infrastructure and critical systems, aiming at the reduction of risk due to earthquakes. Such automatic actions may include stopping elevators at the nearest floor, opening firehouse doors, slowing rapid-transit vehicles and high-speed trains to avoid accidents, to mention some.

Few are the attempts found in literature about engineering applicability of EEW. This scarcity might be related to the fact that the real-time estimation of earthquake source parameters contains considerable uncertainty that may lead to potential economic losses if false or missed alarms are not avoided. However, different state-of-the-art studies regarding decision-making procedures for EEW have suggested more reliable approaches that can potentially reduce the uncertainty in the estimates provided by the system (e.g., earthquake source parameters and ground shaking), reducing the probability of triggering missed/false alarms, and therefore minimising the expected losses.

The potential of designing new real-time advanced building protection applications for EEW is the motivation of this thesis. Mainly, two applications are considered:

1) Design of controlled structural systems using the early warning information, particularly, the use of semi-active devices denominated magnetorheological dampers. A control algorithm that governs the behaviour of the dampers is calibrated to obtain the most favourable response of a benchmark structure equipped with one damper. The results reveal that the developed EEW-based control algorithm can effectively reduce the expected loss of the considered case-study structure.

2) Prediction of shaking demands that can be expected in mid-rise to high-rise buildings, using a simplified continuum building model. A series of illustrative examples show how the newly developed prediction models can be efficiently used, in a Bayesian framework, for building-specific EEW applications based on the (acceleration) response in buildings, such as a) early warning of floor-shaking sensed by occupants; and b) control of elevator in buildings.

The progress of technology and advances in the scientific understanding of engineering and seismology have promoted the rapid development of EEW systems around the world. However, their effectiveness is often limited as they lack the integration between their technical and social components. This thesis also aims at filling this gap to investigate which measures could be needed to increase the organisational resilience of local community stakeholders and the private sector. This topic is explored by implementing a mixed-method approach on the case study Mexico City (Mexico), that can be considered an area at risk due to the combination of high seismic hazard, structural and social vulnerabilities.

This thesis shows the promising applicability of engineered applications of EEW systems and suggests a robust framework for the integration of the technical and societal components of EEW.

# Impact Statement

The importance of early warnings has been highlighted in a number of international documents at various governmental levels. The *2015 United Nations' Sendai Framework for Disaster Risk Reduction* has recognised early warning systems as crucial tools for the prevention of new and reduction of existing disaster risk. Additionally, this framework also highlights that early warning systems must be a priority to improve Disaster Risk Reduction and have to be substantially evolved by 2030. Also, early warnings were emphasized within the *Hyogo Framework for Action (2005–2015): Building the Resilience of Nations and Communities to Disasters*, where they were identified as one (the 2nd) of the five priorities for action.

The last years have seen the dramatic increase of the population in metropolitan areas that are highly exposed and vulnerable to earthquakes. Earthquake Early Warning Systems bear the capacity to activate mitigation actions to be undertaken promptly, before the arrival of ground-shaking to such areas. The systems also have the potential of saving lives by reducing damage and injuries and improving community and organisational resilience by enhancing business continuity operations for both the public and the private sectors.

Therefore, this thesis can offer significant opportunities for impact on *Society*, *Economy* and *Knowledge*.

Concerning the impact on *Society*, the results of this thesis may be used by local community stakeholders (e.g., civil protection) or the public sector, to develop guidelines for improving emergency preparedness towards earthquakes. Findings from this thesis can also provide emergency planners or managers with a better capability and insight for planning emergency rescue actions, based on reliably described real-time scenarios and expected damages. Finally, the results of this thesis also have an impact in strengthening a barely existent cohesion between the technical and the social components of EEW, in some countries where EEW systems are currently operating.

In terms of impact on *Economy*, findings from the thesis provide opportunities for companies, the public, and the private sector, to design and implement businesses continuity and emergency plans related to EEW, as well as engineering applications of EEW systems. As EEW has the capacity of predicting the expected ground-shaking at a given location (e.g., where a critical infrastructure is located), in-advance planning can be developed to produce decision models for actions to take during an EEW, with the main goal of reducing earthquake damage, injuries and deaths.

Regarding the impact on *Knowledge,* the cross-disciplinary approach presented herein promotes the interdisciplinarity for studies related to Disaster Risk Reduction, going beyond the state-of-art in purely physical and engineering approaches for modelling real-time earthquake risk reduction through EEW. The outcomes of this dissertation indeed illustrate that it is possible and viable to investigate the impact of hazards from two or more academic spectra.

# Acknowledgements

The very first day I began this PhD journey, my supervisor, Prof Carmine Galasso, told me “*from this day, until you finish, I am going to be your academic dad in London”.* I think what Carmine has done during my whole PhD can be definitely defined as a fatherhood. I trully believe I do not have the words to show my appreciation and gratitude to him. His time, patience, understanding, and support, definitely are key factors that allowed me to complete this stage of my life. Muchísmas gracias, Carmine. You are definitely a great supervisor, but above that, a fantastic human being.

This thesis was originally planned as a technical study, but with time and so many coffees, Dr Gianluca Pescaroli motivated me to address the challenging social sciences perspective of EEW. Many, many thanks for all the support, help, and friendship that you offered to me so I could finish this thesis, Gianluca. I am eternally grateful for all the efforts you have made for my well-being and for the culmination of my PhD.

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During my whole life I have had four pillars that definitely help me to give my best every single day: my father, my mother, my older brother, and my younger sister. Many thanks for listening to me during the toughest moments I faced while being in London, and for always providing words and advice whenever I have needed them. You are definitely my largest source of inspiration. I love you like you cannot imagine.

I need to thank all those angels I have who send me their blessings and protect me day by day. Since I moved to London, seven years ago, the list has increased, but you are always in my mind and thoughts. I miss you all a lot.

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During 7 years I have met fantastic people in London and UCL, great friends I have shared great and not so good moments with. It is very challenging for me to name you all, I might miss a name and that would be rude to do (also, this acknolwedments section could turn larger than an actual chapter of the thesis…). However, thank you so much to all my friends of the UCL IRDR, UCL CEGE, UCL Mexican Society, and UCL Squash Society. Thanks a lot for the laughs, the tears, the fun, the parties, and for making me feel like at home. This gratitude has to be extended to all my family and friends in Mexico, that have been always sending me support and good wishes.

Last but not least, many thanks to god, for allowing me to live fantastic experiences that have forged the Omar I am at the moment.

# Abbreviations

| | |
|---|---|
| **ASTS** | **Automatic Trip Systems Procedures** |
| **BART** | **Bay Area Rapid Transit** |
| **BEFORES** | **Bayesian Evidence-based Fault Orientation and Real-time Earthquake Slip** |
| **C** | **Cost, Damping** |
| **CCDF** | **Complementary Cumulative Distribution Function** |
| **CISN** | **California Integrated Seismic Network** |
| **DF** | **Decision Function** |
| **DI** | **Destructive Intensity** |
| **eBEAR** | **Earthworm Based Earthquake Alarm Reporting** |
| **EDAS-MAS** | **No explanation available in the literature** |
| **EDP** | **Engineering Demand Parameter** |
| **EDT** | **Equal Differential Time** |
| **EEW** | **Earthquake Early Warning** |
| **ElarmS** | **Earthquake Alarm Systems** |
| **EM** | **Event Monitor** |
| **FinDER** | **Finite-Fault Rupture Detector** |
| **G-FAST** | **Geodetic First Approximation of Size and Time** |
| **GIDS** | **Generalised Interstorey Drift Ratio** |
| **G-larmS** | **Geodetic Alarm System** |
| **GMM** | **Ground-Motion Model** |
| **GMPE** | **Ground-Motion Prediction Equation** |
| **GNSS** | **Global Navigational Satellite System** |
| **GPS** | **Global Positioning Systems** |
| **HAZUS** | **Hazards United States – Federal Emergency Management Agency** |
| **IAEA** | **International Atomic Energy Agency** |
| **IDA** | **Incremental Dynamic Analysis** |
| **IDR** | **Interstorey Drift Ratio** |
| **IEEWS** | **Istanbul Earthquake Early Warning System** |

| | |
|---|---|
| **IM** | **Intensity Measure** |
| **ITACA** | **Italian Accelerometric Database** |
| **JMA** | **Japan Meteorological Agency** |
| **K** | **Stiffness** |
| **KEEWS** | **Korean Earthquake Early Warning System** |
| **L** | **Loss** |
| **M** | **Magnitude, Mass** |
| **MCDM** | **Mutli-Criteria Decision-Making** |
| **MIDR** | **Maximum Interstorey Drift Ratio** |
| **MR** | **Magnetorheological** |
| **OR** | **Organisational Resilience** |
| **P** | **Likelihood of Occurrence** |
| **PBEE** | **Performance-Based Earthquake Engineering** |
| **PBEEW** | **Performance-Based Earthquake Early Warning** |
| **PDF** | **Probability Density Function** |
| **PEER** | **Pacific Earthquake Research Center** |
| **PFA** | **Peak Floor Acceleration** |
| **PGA** | **Peak Ground Acceleration** |
| **PGD** | **Peak Ground Displacement** |
| **PGV** | **Peak Ground Velocity** |
| **PLUM** | **Propagation of Local Undamped Motion** |
| **PRESTo** | **PRobabilistic and Evolutionary early warning System** |
| **PSDA** | **Probabilistic Seismic Demand Analysis** |
| **PSHA** | **Probabilistic Seismic Hazard Assessment** |
| **R** | **Epicentral Distance** |
| **REGARD** | **Real-time GEONET Analysis system for Rapid Deformation monitoring** |
| **RSMS** | **Real-time Strong-Motion Monitoring System** |
| **RTPSHA** | **Real-Time Probabilistic Seismic Hazard Assessment** |
| **Sa(T1)** | **Spectral Acceleration** |
| **SAIVD** | **Semiactive Independently Variable Dampers** |
| **SAS** | **Sistema de Alerta Sísmica (Mexico)** |
| **SASMEX** | **Sistema de Alerta Sísmica Mexicano** |

| | |
|---|---|
| **SASO** | **Sistema de Alerta Sísmica de Oaxaca** |
| **Sd** | **Spectral Displacement** |
| **SDoF** | **Single Degree of Freedom** |
| **SIMBAD** | **Selected Input Motions for Displacement-Based Assessment and Design** |
| **STA/LTA** | **Short-term-average/Long-term-average** |
| **T** | **Fundamental period of vibration** |
| **UNDRR** | **United Nations Office for Disaster Risk Reduction** |
| **UrEDAS** | **Urgent Earthquake Detection and Alarm System** |
| **USGS** | **United Stated Geological Survey** |
| **V** | **Voltage** |
| **VS** | **Virtual Seismologist** |
| **WP** | **Waveform Processing** |

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# Chapter 1. Introduction

## 1.1 Background

Natural hazards' impact affects every year thousands of people around the world, leaving considerable economic losses and a high number of death tolls. According to the Natural Catastrophe Statistics Analysis Tool (NatCatService) of Munich RE[1], from 1998 to 2018, an estimate of 1.2 million people has perished due to the exposure to natural hazards, along with economic losses worth US $3 trillion.

At a time of global changes, with the fast evolution in technology, many different strategies for disaster risk reduction have been taken into consideration by governments and organisations around the globe, aiming for the reduction of human and economic losses and an increment in resilience towards natural hazards. In that aim, one of the rapid growing protection technologies currently implemented is "Multi-hazard Early Warning Systems".

An early warning is defined as "an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events"[2].

Also, early warnings have been worldwide recognised as a measure to reduce disaster risk and increase preparedness, response and recovery to multi-hazard scenarios. In fact, the "*Sendai Framework for Disaster Risk Reduction 2015-2030*", emphasizes that early warnings must be a priority field for disaster risk reduction that has to be substantially evolved by 2030 (UNISDR, 2015).

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[1] https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html

[2] https://www.preventionweb.net/terminology/view/478

Many are the hazards that can be forecasted by an early warning system; some examples are earthquakes, landslides, volcanic eruptions, floods, droughts, and food security.

From the list above, one of the systems that is relatively modern is Earthquake Early Warning (EEW), aiming for earthquake risk reduction. Although the concept of EEW was introduced by J.D. Cooper back in 1868 (Kanamori, 2005; Nakamura and Tucker, 1988), it was not until 1985 when a proper computerised alert network was proposed by Heaton (1985). Heaton suggested that given the slow speed of seismic waves (compared to the velocity of communication-electronic waves), short-period warnings can be provided to trigger automatic safety response actions, once a seismic network has provided estimates of arrival times and intensity of shaking at different sites. Since 1985, with the evolution of the concept proposed by Heaton, some countries around the world have adopted the idea of having a seismic network providing EEW data. Currently, different advanced algorithms can be found in literature for the rapid detection of seismic parameters such as magnitude and location of the earthquake, providing warnings ranging from second to tens of seconds before the arrival of shaking S- waves. The reliable functionality of EEW highly depends on the accurate estimation of ground shaking intensity from a specific seismic source, reason why EEW has been studied mainly by seismologists.

Nowadays, EEW systems are operating in different parts of the world, with different approaches and implementations (Figure 1). In countries such as Mexico (Cuéllar et al., 2017), the United States of America (USA)-West Coast (Given et al., 2018), Japan (Hoshiba et al., 2008), Turkey (Alcik et al., 2009), Romania (Marmureanu et al., 2011), Taiwan (Hsiao et al., 2009), South Korea (Sheen et al., 2017), India and China (Ji et al., 2019), and India (Kumar et al., 2014), EEW systems provide public warnings. They are also real-time tested for implementation in Italy (Zollo et al., 2014a), Switzerland (Cua et al., 2009), Chile (Crowell et al., 2018), Israel (Nof and Allen, 2016), Nicaragua (Strauch et al., 2018), Spain (Pazos et al., 2015), Slovenia and Austria (Picozzi et al., 2015a), Greece, New Zealand and Iceland (Behr et al., 2016), as well as in Costa Rica and El Salvador (Allen and Melgar, 2019).

The warnings provided by the systems allow for the implementation of fast protection actions carried out by individuals like ‘Drop-Cover-Hold’, or the evacuation of buildings if the lead time is long enough. Nevertheless, the information provided by the system could also be used by earthquake engineers as EEW seems to bear a powerful potential for the immediate automatic activation of protection measures for infrastructure and critical systems, with the final objective of reducing casualties and economic losses due to earthquakes. The warning time available before the arrival of the earthquake depends on the distance between the earthquake’s epicentre and the target area to be protected. Therefore, the activation of any automatic action is firmly based on the available warning time. The mitigation actions that can be activated might include stopping elevators at the nearest floor, opening firehouse doors, slowing rapid-transit vehicles and high-speed trains to avoid accidents, shutting down pipelines and gas lines to minimize fire hazards, shutting down manufacturing operations to decrease potential damage to equipment, saving vital computer information to avoid data losses, etc.

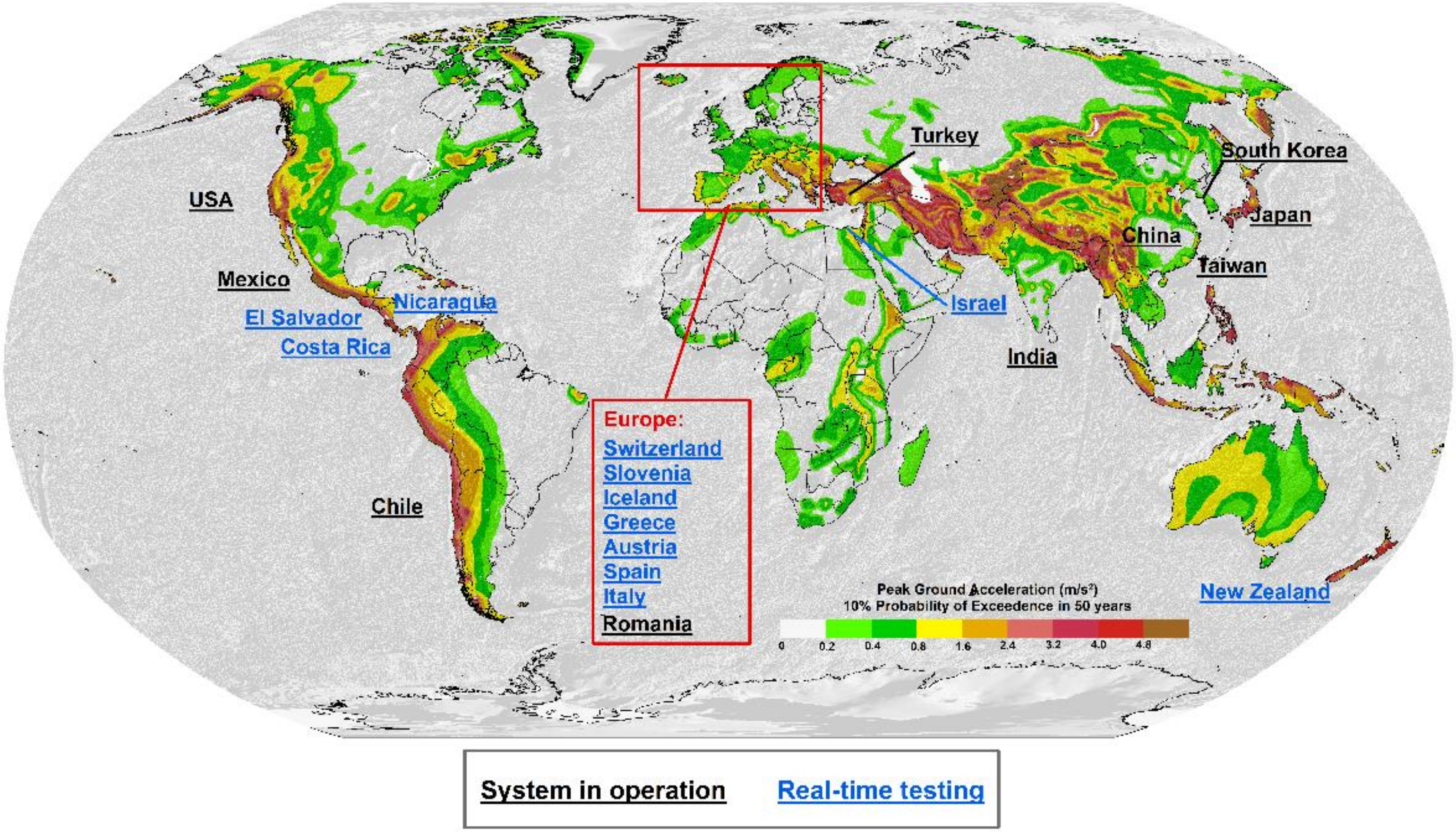

*Figure 1. Earthquake Early Warning Systems in the world. Black-coloured countries indicate operative systems, that provide public warnings. Blue-coloured words represent nations where the systems currently are under testing.*

Few are the attempts found in literature implementing and designing engineering applications considering EEW. Mainly, control of elevators, control of trains, protection of critical infrastructure (e.g., gas and oil pipelines), are the focus of these investigations, where the actions are triggered if the EEW system detects that a critical ground-shaking intensity value will be exceeded. The listed strategies reduce the exposure of the systems leading to the reduction of losses. However, they do not avert the inherent damage (vulnerability) due to ground shaking (Iervolino et al., 2007b).

One of the significant reasons for which engineering applicability of EEW is so scarce is because the real-time estimation of magnitude and location of the earthquake contains considerable uncertainty, that may lead to potential economic losses if false or missed alarms are not avoided (for example, stopping high velocity trains could delay the timetable creating economic losses and inconvenience in passengers; shutting down a power plant after a false alarm might generate considerable economic losses due to business interruption). However, different state-of-the-art studies regarding decision-making procedures for EEW systems have suggested more accurate/reliable approaches that potentially reduce the uncertainty in missed and false alarms, and therefore in the expected losses (e.g., loss-based approach). From an engineering perspective, these new decision-making procedures seem to be a powerful tool for the design of applications aiming for the real-time protection of structures/infrastructure.

The potential of designing new real-time advanced building protection applications for EEW systems, based on the framework of a performance-based model, is one of the main motivations of this project. This report will introduce the methodology followed to develop two new real-time structural engineering applications, discusses the results obtained and provides strong evidence for the future evolution of the applications proposed (and new ones).

The progress of technology and advances in the scientific understanding of engineering and seismology have promoted the rapid development of EEW systems around the world. However, their reliability is often limited as they lack the integration between their technical and social components (Basher, 2006). The last chapter of this thesis aims at filling this gap, intending to investigate which measures could be needed to increase the organisational resilience of local community stakeholders and the private sector. This topic is explored in the last chapter of this report by implementing a mixed-method approach on the case-study Mexico City (Mexico), that can be considered an area at risk due to the combination of high seismic hazard, structural and social vulnerabilities.

## 1.2 Scope and aims of research

This thesis is concerned with the investigation of the cross-disciplinary components of Earthquake Early Warning Systems. The scope of the dissertation is twofold, divided in two different (but correlated) segments: 1) the technical applicability of EEW, focusing on an engineering/seismological perspective and 2) the integration of the physical/technical components of EEW systems with the corresponding/relevant socio-organisational components, adopting a perspective of the social sciences .

The first part concerns the design of two novel real-time advanced applications for the protection of buildings, using the estimates provided by EEW systems. Application 1 looks at the feasibility of combining semi-active structural control with EEW, to minimise the losses in a structure about to be struck by an incoming earthquake. In specific, a semi-active control device known as Magnetorheological (MR) Damper is used for the study, as this type of device can generate relatively large damping forces depending on very low electric inputs, without inducing instability to the structure. The main aim of developing this application is to design an algorithm that regulates the command voltage of the MR damper, based on the ground shaking predicted by the EEW system. The novelty herein is that the algorithm is developed, adopting a performance-based approach in which losses govern the efficiency of the algorithm. The loss-based approach allows to compute the most favourable performance of the structure considering a combination of different Engineering Demand Parameters (EDP; e.g., Peak Floor Acceleration and

Interstorey Drift Ratio), rather than classic approaches where the performance is based on singular EDPs (e.g., Maddaloni et al. 2013). Application 2 refers to the development of a new approach for real-time building response assessment based on the information provided by an EEW system. EEW systems (particularly ’regional’ ones) typically provide early estimates of earthquake magnitude (M) and hypocenter location (i.e. source-to-site distance, R) as well as ground-motion intensity measures (IMs) at target sites and warning time to target users. A common approach to real-time IM estimation is to use ground-motion models (GMM) based on the real-time M, and R estimates from the EEW system. Current practice consists on triggering real-time earthquake mitigation actions when the expected IM, computed based on EEW information, exceeds a predefined IM threshold.

Nevertheless, the shaking experienced in mid-to high-rise buildings is generally significantly different from that on the ground, and it also differs from one building to another, depending on the building (dynamic) characteristics. Therefore, this application proposes a set of new empirical prediction equations, based on Italian accelerometric data, correlating EDPs for case-study buildings to the source- and site-specific parameters (e.g., M, R, and soil type). To this aim, a simplified continuum building model consisting of a combination of a flexural beam and a shear beam is used. By just modifying a few structural parameters, such a simplified model can account for a wide range of deformation modes in actual buildings, allowing the accurate estimation of lateral displacement and acceleration demands in a structural system.

The second part focuses on the development of a new approach for the integration of the technical and the socio-organisational components of EEW. The aim herein is to produce a better understanding of the social components of EEW, and their interactions with the existing technical components (engineering and seismological) that are used on the field, to produce new practices and guidelines for increasing organisational resilience. In particular, the following questions are to be answered: a) *What are the interactions* *between the technical components and the socio-organisational components of EEW*? b) *What could be required in the socio-organisational domains to have effective EEW systems*? c) *What information and training are needed by community organisations, business, and the private sector in order to respond and adapt more effectively to the dissemination of earthquake early warnings?* To answer these questions, a mixed-method approach is implemented on the case study Mexico City (Mexico), that can be considered an area at risk due to the combination of high seismic hazard, structural and social vulnerabilities. In particular, a convergent mixed-method approach is adopted herein as it allows the collection and analysis of qualitative and quantitative data simultaneously. In order to qualitatively and quantitively assess the value of the Mexican EEW system to the key sectors of Mexico City's government, critical infrastructure and business community, two instruments were considered for the collection of data: a) semi-structured interviews with representatives of organisations from the private or public sector based in Mexico City; and b) online questionnaires distributed through a convenience sample and with voluntary participation, targeted also at representatives of the public and private sector of Mexico City. For the construction of the on-line questionnaire, this thesis also develops a novel (Likert) scale designed for benchmarking questionnaires' answers in the fields of disaster risk reduction, business continuity management, and organizational resilience. This new scale responds to a need of scholars and practitioners of having a simple scale of reference to assure consistency across disciplinary fields. Introducing answers from 0-3, the proposed simple-to-use tool substitutes more complex scales (e.g., from 1 to 7) that may be unsuitable to use on in-depth analyses of quantitative data.

## 1.3 Thesis outline

Chapter 2 introduces the basic functioning principle of Earthquake Early Warning Systems and the different types of these systems. In addition, a description of the current EEW systems operating around the world and their relevant estimation algorithms is discussed, along with a summary of the state-of-the-art engineering applications of EEW at present in practice or proposed.

Chapter 3 explores the current interactions between the technical and socio-organisational components of EEW systems. This includes a discussion of specific evidence on the case-studies of Italy, California, Japan and Mexico, representing different maturity levels for EEW systems.

Chapter 4 presents the methodology followed to evaluate the feasibility of designing controlled structural systems using the early warning information, in particular, the use of semi-active devices denominated MR dampers. An application referring to a simple structure is developed, comparing the seismic risk in two cases: a) structure equipped with MR dampers and EEW system; and b) structure with traditional passive control devices (e.g., seismic isolation).

Chapter 5 discusses the prediction of the characteristics of shaking that can be expected in mid-rise to high-rise buildings, using a simplified continuum building model consisting of a combination of a flexural beam and a shear beam. In particular, new empirical prediction equations, based on Italian accelerometric data, are developed correlating Peak Floor Acceleration and peak Interstorey Drift demands, for a set of case-study buildings to earthquake-related parameters. A series of illustrative examples show how the newly developed prediction models can be efficiently used for building-specific EEW applications.

Chapter 6 introduces a new-developed, simple-to-use, rating tool that can be used for benchmarking responses in questionnaires, to assess, for example, disaster risk reduction, gaps in operational capacity, and organizational resilience (e.g., to be implemented in questionnaires regarding the efficiency of EEW systems in organisational resilience).

Chapter 7 investigates which measures could be needed to increase the organisational resilience of local community stakeholders and the private sector. Specifically, this chapter analyses the case-study of Mexico City (Mexico), that can be considered an area at risk due to the combination of high seismic hazard, structural and social vulnerabilities. Here, EEW has been developed by the authorities, but the need for increasing their efficiency is widely recognised. The goal is to provide some new and impact-oriented insight on the connection between their technical and social components.

Finally, Chapter 8 summarises the final remarks derived from this thesis and proposes possible future lines of research and future work.

The chapters of this thesis are developed to be mostly self-contained because they are published as individual journal/conference articles. Therefore, repetition in some chapters such as introductions and background material can be found throughout the thesis. Additionally, notational conventions were chosen to be simple and clear under the topic of each chapter, rather than for the thesis as a whole; consequently, the notational conventions may not be strictly identical for each chapter. Apologies are offered in advance for any confusion this might cause when reading the thesis as a continuous document.

# Chapter 2. EEW Systems: physical grounds, technical concepts, methods and perspectives

## 2.1 Earthquake Early Warning: Principle and definitions

Earthquake Early Warning (EEW) Systems are combinations of real-time seismic instruments, methodologies and data processing software that are able to provide rapid measures of potential ongoing earthquakes in the early stage of fault rupture and issue real-time warnings to public or end users in large urbanised areas. The alarm triggered is considered a solution to reduce exposure and vulnerability due to earthquake risk, improving emergency preparedness and minimising economic and human losses (Heaton, 1985; Strauss and Allen, 2016; Wieland, 2001).

The basic functioning idea of an earthquake early warning system relies on the velocity of the seismic waves propagating from the rupturing fault during an earthquake (Satriano et al., 2011b). When the rupture occurs, P- waves and S- waves spread through the shallow layers of the earth (Figure 2). P-waves travel faster than S- waves, however S- waves, due to their large amplitude, are more damaging than P-waves, leading to ground shaking. An EEW system requires a dense seismic network deployed, close to the area where large earthquakes are expected, where the arrival of seismic waves are recorded. When the earthquake occurs, the seismic stations detect the arrival of P- waves and send the recordings at the speed of light to a central station, where data processing software calculates the estimated arrival of S- waves by considering the difference in velocity of the waves. The difference in arrival of P- waves and S- waves has been defined as ‘lead time’ and tends to range from few to tens of seconds. The actual/effective warning time depends mainly on the distance of the target structure/infrastructure with respect to the earthquake source. This allows for real-time seismic risk-mitigating actions. From the engineering perspective, if an earthquake is going to strike a target structure (or infrastructure/infrastructure component) and induce a response/damage level of enough severity, then planned mitigating actions can be taken immediately in order to limit potential losses. For instance, individuals can use the alert time to Drop-Cover-Hold or move to safer locations within a building, reducing injuries and fatalities, or if alert time allows, evacuate hazardous buildings. Such a warning time also (and especially) allows for many types of automated actions: stopping elevators at the nearest floor and opening the doors, opening firehouse doors, slowing high-speed trains to avoid accidents/derailments, turning streetlights red - preventing cars from entering hazardous structures such as bridges and tunnels, shutting down gas pipelines to minimize fire hazards, shutting down manufacturing operations to decrease potential damage to equipment, saving vital computer information to avoid data losses, etc. This is not an exhaustive list but rather a snapshot of critical applications that could benefit from EEW.

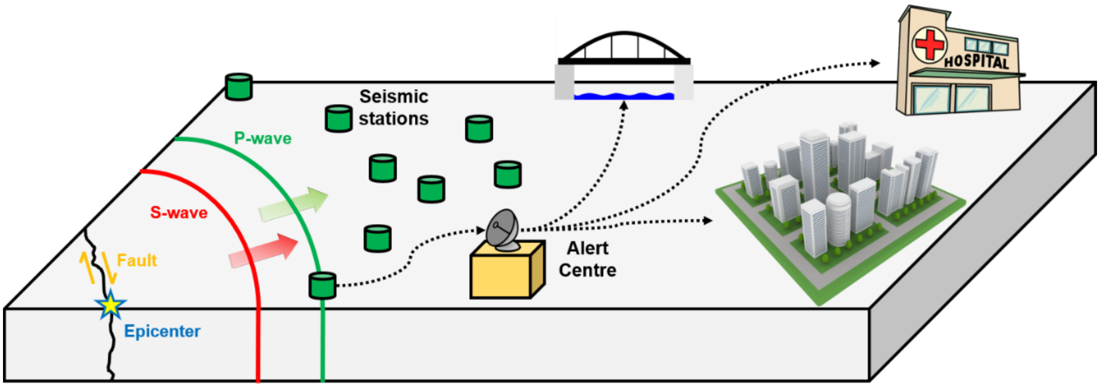

*Figure 2. The basic principle of EEW*

Research and development of EEW applications have not yet been emphasized in the engineering community, although very rapid improvements of EEW are being observed in the seismology community, as also noted above. In practice, two fundamental problems of EEW restrict its actual applications: 1) short warning time, particularly in epicentral areas, and 2) large uncertainty on the predicted ground motion (and consequent damage/loss). Regarding 1), to maximize warning time, the system must minimize delays in data acquisition/processing, communication, and delivery of alerts (e.g., increasing the number and density of seismic stations). Regarding 2), EEW information always involves some uncertainty due to the real-time estimation of source parameters and traditional uncertainties involved in Probabilistic Seismic Hazard Analysis (or PSHA; Iervolino et al., 2006). Some EEW applications may produce a substantial economic loss if a false alarm occurs (e.g., due to business interruption), eventually affecting large communities (e.g., in the case of emergency stop of lifelines). On the other side, there is a complex trade-off between the potential costs of false (and missed alarms) and the available warning time: as the seismic network collects more data on the earthquake, predictions will improve, but the time until shaking will decrease (Iervolino et al., 2009). The short warning time means that automated decision and mitigation actions are usually the preferred (or the only) option. From an engineering perspective, the real-time probabilistic assessment of source parameters (e.g., magnitude and source-to-site distance) and/or earthquake-induced ground-motion IMs, is the first step from real-time seismology to structural performance. However, it is well known that the IM may be poorly informative with respect to the structural response, consequent damage level and expected loss: the real-time prediction of an IM is not a reliable basis to decide whether to issue an alarm. Hence, quantifying in real-time the structural response or even the loss (i.e., costs) for a structure of interest is a sounder basis for the warning management/alarm threshold setting.

This can be done within the framework of the performance-based earthquake engineering (PBEE; e.g., Porter et al. (2007), as discussed in detail in Iervolino (2011), estimating the seismic performance of structure/infrastructure/engineering systems in terms of metrics of interest to stakeholders (i.e., ‘dollars, deaths, and downtime’), considering individual building/infrastructure components (structural, non-structural and contents), and accounting for all important sources of uncertainty. To achieve this, accurate yet (computationally) efficient regional structural response prediction methods must be coupled with real-time seismic hazard analysis to assess, in real-time, seismic damage and associated losses in order to trigger planned mitigation actions (e.g., alerting occupants, controlling elevators, etc). Some recent studies (e.g., Maddaloni et al., 2013; Velazquez et al., 2017) have also discussed the control of structures as a possible advanced structural engineering application of EEW, especially in areas where the available warning time is very short (near the so-called blind-zone). For instance, a building could change its dynamic properties within a few seconds (or milliseconds) to better withstand the approaching ground shaking. The combined use of EEW and structural control, particularly semi-active devices, may reduce the structural vulnerability (and resulting losses) of specific systems. For instance, critical buildings which must be operational for emergency management purposes right after the event (e.g., hospitals, fire stations, or lifelines) could benefit from such systems.

It is worth noting that a PBEE approach can allow one to compare the expected losses corresponding to the three different possible outcomes of any EEW system: 1) performing an accurate mitigation action; 2) triggering false alarms; and 3) missing alarms. As discussed in Iervolino (2011), regardless of the applications to be designed, three essential design variables must be considered to assess the feasibility of implementing a given action: a) the required warning time; b) the false alarm acceptability; and c) the expected loss mitigation and related costs.

## 2.2 Regional and On-site EEW systems

According to the configuration of the networks/sensors, EEW systems can be conceptually classified as regional and on-site systems; Figure 3. The following sections describe the specific features of each system and provide a few examples of locations where they have been installed.

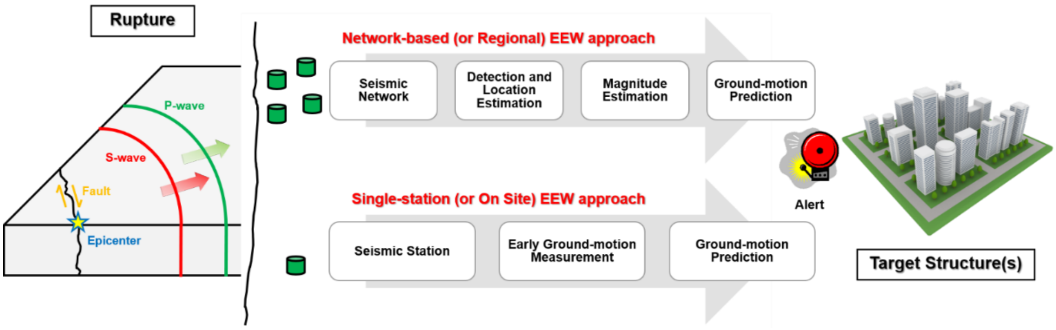

*Figure 3. The two possible approaches to EEW. In the network-based approach, the lead-time is equal to the S-arrival time at the target minus the first-P at the network minus any processing/computation time; in the single-station approach the lead-time is equal*

### 2.2.1 Regional EEW systems

A regional EEW system is based on a dense sensor network covering a geographical area of high seismicity. When an earthquake occurs, the relevant source parameters (e.g., event location and magnitude) are estimated from the early portion of recorded signals at sensors close to the rupture; estimates of the source parameters are used to predict, with a quantified confidence, a ground-motion IM at a distant site where target structures of interest are located. Regional EEW system typically require a number of stations that have triggered the arrival of the P-wave signal to provide stable early estimates of earthquake location (and source-to-site distance, R), earthquake magnitude (M), and ground-motion distribution in terms of the selected ground-motion IM.

It is worth noting that methodologies for regional EEW generally assume a point-source model of the earthquake source and isotropic wave amplitude attenuation. These assumptions are often inadequate to represent the earthquake source of large earthquakes and wave amplitude attenuation effects, introducing significant biases in the real-time estimation of earthquake location and magnitude. Within this context, new developments have been proposed, such as the use of continuous Global Positioning Systems (GPS) measurements and methodologies to estimate fault rupture extent in real time by classifying stations into near source and far source. Another option is a fast-kinematic inversion of the rupture process, searching for the fault geometry, the focal mechanism, and the slip distribution on the fault plane.

### 2.2.2 On-site EEW systems

Site-specific, or on-site, EEW system consist of an array of sensors or a single sensor located in the vicinity of a single target site or structure/infrastructure of interest. Site-specific systems provide estimates of peak-ground-motion IMs (e.g., peak ground acceleration, PGA, or peak ground velocity, PGV) based directly on the amplitude and predominant period of the initial recorded P-wave signal. This is achieved by implementing empirical regressions correlating the measurements obtained on the P-wave recordings and the final IM. Adopting this type of relationships allows a user for faster computations/ warning issuance as independent magnitude estimates are not required, differently to the regional EEW approach described above.

Generally, on-site EEW systems are threshold-based, i.e., the warning is given when the measured P-wave peak amplitude exceeds a pre-defined critical threshold that is based on the predicted S-wave peak ground-motion amplitude (This critical threshold is usually related to the ground acceleration amplitudes recorded by the EEW system, but might also be associated to the displacement or acceleration demands that can induce damage (losses) to the case-study structure/infrastructure; Zollo et al., 2014b; Velazquez et al., 2017). However, small-to-moderate earthquakes ($M$<6) might produce large amplitudes due to high-frequency spikes, and therefore false alarms can be triggered. To overcome this issue, a different approach is considered in which combinations of P-wave peaks and the P-wave predominant period are merged into a single proxy to provide more confident warnings (e.g., Wu and Kanamori, 2005). This idea has been furthermore updated by Colombelli et al. (2012a) and Zollo et al. (2010), who have proposed a threshold-based EEW methodology combining real-time measurements of the average period ($\tau_c$) of the first seconds of the P- wave signal, and the peak displacement amplitude ($P_d$) of initial P- and S-wave triggers, at sensors located at incrementing distances away from the epicentre of the earthquake. The measured values of $P_d$ and $\tau_c$ are compared to threshold values, which are set for a specific minimum magnitude and instrumental intensity. Finally, at each recording site, an alert level is assigned based on a decisional table with four levels defined upon threshold values of the parameters $P_d$ and $\tau_c$.

A variant of on-site approaches also exists, denominated front-detection system; it resembles a fence against seismic waves, where sensors are strategically located between the earthquake’s likely source and the target to be protected. This type of system is especially convenient when the seismic sources are at a significant distance away from the target to be protected. Front-detection systems provide the opportunity to maximise the warning time, allowing the activation of safety procedures before the arrival of ground shaking (Iervolino, 2011). An example of front-detection system is the one installed on the west coast of Mexico, that serves as a barrier-type network and provides warnings for Mexico City (Espinosa-Aranda et al., 2011). Mexico City is located, on average, 300 km away from the west coast area of the country, where the most significant potential seismic sources have been localised (Asgary et al., 2007; Lockman, 2005; Wurman et al., 2007).

Front-detection systems issue alerts when two or more nodes of the array record a ground acceleration amplitude larger than a defined critical value (Zollo et al., 2014b). For typical regional distances, the peak acceleration at the fence nodes is expected to be associated with the S-wave train, so that the distance between the network and the target is set to maximize the lead time, which for this instance is the travel time of S-waves from the fence to the target site. Similar to the on-site systems, front-detection systems do not estimate earthquake source parameters (magnitude and location), as a local measure of the effects (e.g., the ground motion) is already available (e.g., Iervolino, 2011).

P-wave-based, regional, and on-site EEW methods/systems can be integrated in a unique alert system, which can be used in the very first seconds after a moderate-to-large earthquake to determine the earthquake location and magnitude and to map the most probable damaged zone, using data from receivers located at increasing distances from the source.

## 2.3 Current state-of-the-art methodologies and developments in EEW

This section describes the most popular current algorithms implemented for the real-time detection of the event, estimation of the earthquake source parameters and ground shaking, as well as the methodologies recently used for triggering alerts. The following summary is based in the studies carried out by Allen and Melgar (2019), Satriano et al. (2011b), Zollo et al. (2014), and Cremen and Galasso (2020).

### 2.3.1 Event detection and estimation of the location

The following section summarises the most popular current methods for event detection and EEW estimation of event locations.

Procedures used in Point-source regional EEW systems.

Two different approaches have been implemented for point-source systems.

1) Estimation of location, using only the information from stations that have been triggered by the arrival of P-waves (Table 1). This method is theoretically straightforward and computationally efficient to implement, but it only uses information from triggered stations, which means it is less certain when compared to the location estimates from the procedure of Table 2.

*Table 1: Estimating location, using only information from triggered stations*

| **Description of Method** | |
|---|---|
| Seismic arrivals at a station are detected using a picker method, such as the short-term-average/long-term-average STA/LTA procedure (Allen, 1978). Once a sufficient number of stations have triggered (in accordance with the underlying EEW algorithm), the location is estimated using a grid search routine to minimise the residuals between observed seismic phases and those predicted from a velocity model. | |
| **Inputs** | **Outputs** |
| P-wave arrival times at triggered stations; Velocity model; Seismic station locations | Epicentre /hypocentre location estimate |
| **Relevant algorithms and references** | |
| ElarmS (Allen et al., 2009a; Chung et al., 2019; Kuyuk et al., 2014; Wurman et al., 2007), in the USA, Chile and Israel; eBEAR (Chen et al., 2015; Hsiao et al., 2009; Wu and Teng, 2002) in Taiwan; and the Beijing EEW system (Peng et al., 2011), in China. | |

2) Estimation of location, using the information from both triggered and non-triggered stations (Table 2). Although the estimates from this procedure are

more reliable than those of Table 1, this method is more challenging to implement in seismic networks that have non-uniform station telemetry delays (Cua et al., 2009).

*Table 2: Estimating location, using information from both triggered and non-triggered stations*

<table>
<tr><th colspan="2">Description of Method</th></tr>
<tr><td colspan="2">When a seismic arrival is detected at the first station, the location is initially constrained either by the geometric surface that represents the set of all locations closer to the station than any other station in the network, or characteristics of the early waveform envelope. Once two stations have triggered, location uncertainty is reduced to a conditional surface based on the time between the P-wave detections. The location can be estimated directly when the third station is triggered. Alternatively, grid search routines are used to increasingly constrain the location after the second or third trigger.</td></tr>
<tr><td><b>Inputs</b></td><td><b>Outputs</b></td></tr>
<tr><td>P-wave arrival times at triggered stations; Velocity model; Seismic station locations</td><td>Epicentre/ hypocentre location estimate</td></tr>
<tr><td colspan="2"><b>Relevant algorithms and references</b></td></tr>
<tr><td colspan="2">JMA (Horiuchi et al., 2005; Rydelek and Pujol, 2004), in Japan; Virtual Seismologist (Cua, 2005; Cua et al., 2009; Cua and Heaton, 2007), in the USA, Switzerland, Costa Rica, El Salvador y Nicaragua; and PRESTo (Satriano et al., 2008, 2011a), in Italy, Austria, Slovenia and Spain.</td></tr>
</table>

<u>On-site EEW system methodology</u>.

The on-site method (Table 3) is very rapid and thus useful for near-source target sites, however it is significantly less accurate than the rest of the procedures described in this section, since it relies on data from only one seismic station.

*Table 3: Estimating location from a single seismic station*

| **Description of Method** | |
|---|---|
| The distance is estimated from empirical equations, which include variables such as the peak P-wave amplitude and an estimate of the magnitude. | |
| **Inputs** | **Outputs** |
| Required parameters for empirical equations (e.g. peak P-wave amplitude); | Epicentre/Hypocentre estimate |
| **Relevant algorithms and references** | |
| UrEDAS (Nakamura, 1988; Nakamura and Saita, 2007) in Japan; and EDAS-MAS (Peng et al., 2013), in China. | |

<u>Finite-fault algorithms</u>.

The outputs from finite-fault algorithms tend to be the most accurate in comparison with the point-source and on-site methodologies, however they typically take longer to compute. This might represent a disadvantage for EEW systems, as longer computation times can reduce lead times.

Two finite-fault procedures have been implemented for constraining the earthquake's location:

1) Estimating the earthquake centroid by using ground motion image-recognition techniques (Table 4).

*Table 4: Estimating earthquake centroid, using ground motion image-recognition techniques*

| **Description of Method** | |
|---|---|
| An image ($I$) of the observed spatial peak ground motion amplitude distribution is compared to theoretical templates ($T$), which are calculated from a ground-motion model for line sources of varying length. The optimum $T$ is then found by minimising the misfit between $T$ and $I$, and the centroid of the corresponding line source is equivalent to the centroid of the earthquake. | |
| **Inputs** | **Outputs** |
| Theoretical ground motion templates, modelled from GMMs; Observed (high frequency) ground motion amplitudes; Seismic station locations | Centroid estimate |

| **Relevant algorithms and references** |
|---|
| FinDER (Böse et al., 2012, 2015, 2018), in the USA, Switzerland, Chile, Costa Rica, El Salvador and Nicaragua). |

2) Estimating earthquake depth, using geodetic observations (Table 5).

*Table 5: Estimating earthquake depth, using geodetic observations*

| **Description of Method** | |
|---|---|
| Initial estimates of earthquake depth are obtained from grid searches based on peak ground displacement (PGD) scaling relationships, using information on magnitude and pre-computed epicentral distance estimates. Final depth estimates are computed from a centroid moment tensor calculation, using static offsets from GPS data. | |
| **Inputs** | **Outputs** |
| Epicentral distance estimates (from another EEW algorithm); GPS displacement waveforms; Green's functions | Depth estimate |
| **Relevant algorithms and references** | |
| G-FAST (Crowell et al., 2013, 2018; Melgar et al., 2015), in the USA and Chile. | |

Computation of uncertainties.

Two of the point-source algorithms previously described account for uncertainties when calculating estimates of the event's location. PRESTo (Table 2) computes a Probability Density Function (PDF) for the location of the hypocentre, that is parametrised by a mean estimate and a covariance matrix that captures spatial uncertainty. Virtual Seismologist (Table 2) adopts a Bayesian approach, in which the location and magnitude of the event are jointly conditioned on the already available set of ground motions, and the PDF represents an existing level of knowledge on relative earthquake probability.

### 2.3.2 Magnitude Estimation

This section introduces the most common procedures for estimating the magnitude of the event.

Point-source methodologies.

Two different approaches are currently being implemented for the real-time estimation of the magnitude of an earthquake:

1) Estimation of magnitude from information obtained in the very initial portion of seismic waveforms. This method (Table 6) takes advantage of empirical relationships between the magnitude of the event and physical characteristics of its initial P-waves. The relationships used herein have been found to saturate for large magnitudes.

*Table 6: Estimating magnitude from information in the very initial portion of seismic waveforms*

| **Description of Method** | |
|---|---|
| The magnitude is estimated from the amplitude (e.g. peak displacement) and/or the frequency content (e.g. characteristic period) of the initial few seconds of the incoming P-wave train, using empirical relationships. Estimates are typically averaged over a number of seismic stations | |
| **Inputs** | **Outputs** |
| Initial seismic waveform; Magnitude-ground motion empirical relationship | Magnitude estimate |
| **Relevant algorithms and references** | |
| ElarmS (Allen and Kanamori, 2003; Tsang et al., 2007; Wu and Zhao, 2006; Wurman et al., 2007), in the USA, Chile and Israel; Virtual Seismologist (Cua, 2005; Cua et al., 2009; Cua and Heaton, 2007) in the USA, Switzerland, Costa Rica, El Salvador and Nicaragua; REWS (Böse et al., 2007; Ionescu et al., 2007; Marmureanu et al., 2011), in Rumania; eBEAR (Chen et al., 2015; Hsiao et al., 2009), in Taiwan; KEEWS (Sheen et al., 2014, 2017), in South Korea; the Beijing EEW system (Peng et al., 2011), in China; and the EEW system for Souther-Iberia (Carranza et al., 2013), in Spain. | |

2) Estimating the magnitude of large earthquakes by increasing time windows of initial seismic waveforms. This method (Table 7) uses a longer waveform

window of that in Table 6. This is implemented to avoid saturation of the aforementioned relationships.

*Table 7: Estimating magnitude from information in increasing time windows of initial seismic waveforms*

| **Description of Method** | |
|---|---|
| The method is similar to the procedure outlined in Table 6, except that the amplitude and frequency content parameters of the empirical relationships are measured over larger/increasingly expanding time windows, and thus may also incorporate information from S-waves. | |
| **Inputs** | **Outputs** |
| Initial seismic waveform; Magnitude-ground motion empirical relationship | Magnitude estimate |
| **Relevant algorithms and references** | |
| PRESTo (Colombelli et al., 2012b, 2014, 2015; Lancieri and Zollo, 2008; Satriano et al., 2011a; Zollo et al., 2006), in Italy, Austria, Slovenia and Spain; SASMEX (Cuéllar et al., 2017; Suarez et al., 2009), in Mexico; and JMA (Kamigaichi, 2004) in Japan. | |

On-site EEW system methodology.

This algorithm (Table 8) allows for a rapid computation of the magnitude at sites close to the epicentre. However, it is less reliable than the rest listed in this section, due to its dependence on the data provided by a single station.

*Table 8: Estimating magnitude from initial characteristics of a single seismic waveform*

| **Description of Method** | |
|---|---|
| The magnitude is estimated from the amplitude (e.g. peak displacement) and the frequency content (e.g. the predominant period) of the initial few seconds of the incoming P-wave train, using empirical relationships | |
| **Inputs** | **Outputs** |
| Required amplitude and frequency parameters | Magnitude estimate |
| **Relevant algorithms and references** | |
| UrEDAS (Nakamura, 1988; Nakamura and Saita, 2007); OnSite (Böse et al., 2009; Kanamori, 2005), in the USA; and EDAS-MAS (Peng et al., 2013), in China | |

Finite Fault algorithms.

These algorithms provide the most realistic estimation of the magnitude of the earthquake, as they consider measurements of the entire fault plane.

Two different implementations of finite-fault algorithms are currently operating in some EEW systems:

1) Estimating the earthquake magnitude by using ground motion image-recognition techniques (Table 9).

*Table 9: Estimating magnitude from rupture length*

| **Description of Method** | |
|---|---|
| The magnitude is estimated from an empirical magnitude-rupture length equation (e.g., Wells and Coppersmith 1994). | |
| **Inputs** | **Outputs** |
| Rupture length estimate | Magnitude estimate |
| **Relevant algorithms and references** | |
| FinDER (Böse et al., 2012), in the USA, Switzerland, Chile, Costa Rica, El Salvador and Nicaragua. | |

2) Estimating magnitude using geodetic observations (Table 10).

*Table 10: Estimating magnitude from geodetic observations*

| **Description of Method** | |
|---|---|
| Static offsets are obtained from displacement time series that are measured using a geodetic data collection system, such as GPS or Global Navigational Satellite System (GNSS). An inversion technique recovers slip estimates from the static offsets, which are then used to calculate the magnitude | |
| **Inputs** | **Outputs** |
| Fault geometry estimates; GPS/GNSS displacement waveforms; Seismic station locations; Remaining parameters of the inversion method used (e.g. Green's functions, station seismograms) | Magnitude estimate |
| **Relevant algorithms and references** | |

G-larmS, BEFORES and G-FAST (Allen and Ziv, 2011; Colombelli et al., 2013; Crowell et al., 2009, 2012, 2016; Grapenthin et al., 2014b, 2014a; Minson et al., 2014; Ohta et al., 2012; Wright et al., 2012; Zhang et al., 2014), in the USA; G-FAST (Crowell et al., 2018), in Chile; and GARD (Kawamoto et al., 2016, 2017) in Japan

Computation of uncertainties.

Different algorithms carry out the computation of uncertainties in magnitude estimates. PRESTo represents the magnitude as a normal PDF; the average value is calculated from an empirical relationship between the initial characteristics of the P-wave and the magnitude, and the standard deviation depends on errors in the coefficients of such empirical relationship, as well as uncertainty in the distance estimate. Virtual seismologist conditions the magnitude and the location on the set of observed ground motions, as previously described in Chapter 2.3.1. The EEW of Spain, G-FAST, OnSite, and EDAS-MAS, consider confidence intervals on the median of magnitude estimates, which are equal in width to two standard deviations of the empirical relationship adopted to obtain the magnitude.

### 2.3.3 Ground shaking estimation

This section presents the most common EEW approaches currently adopted for the real-time estimation of ground shaking.

Ground shaking estimation in Regional EEW systems.

Three different approaches are used to estimate ground shaking in Regional EEW systems. The most common IMs predicted by these algorithms are PGA and PGV.

1) Estimation of ground shaking using empirical attenuation relationships. The estimation of ground shaking (Table 11), in terms of IMs, is typically computed using empirical attenuation relationships, considering the earthquake source

parameters available after implementing the approaches previously described. IMs quantify the probable damage potential of an earthquake-induced ground motion with respect to a specific engineered system (e.g., a structure), and can be used to predict the associated seismic response of the system (Baker and Allin Cornell, 2005).

*Table 11: Estimating ground shaking from attenuation equations*

| **Description of Method** | |
|---|---|
| Source distances to target sites of interest are first computed based on earthquake location estimates. Empirical attenuation relations (e.g., GMMs) are then used in combination with these distances and the magnitude estimate, to calculate spatial estimates of ground shaking. | |
| **Inputs** | **Outputs** |
| Magnitude estimate; Location estimate; Remaining parameters of the attenuation relationship used (e.g. site condition) | Ground motion amplitude estimates |
| **Relevant algorithms and references** | |
| ElarmS (Allen et al., 2009a), in the USA, Chile and Israel; PRESTo (Satriano et al., 2011a), in Italy, Austria, Slovenia and Spain; Virtual Seismologist (Cua, 2005), in the USA, Switzerland, Costa Rica, El Salvador and Nicaragua; and JMA (Kamigaichi, 2004), in Japan. | |

2) Estimation of ground shaking from ground motion recordings (Table 12).

*Table 12: Estimating spatially distributed ground shaking from ground motion recordings*

| **Description of Method** | |
|---|---|
| Recorded ground motion estimates are translated into spatially distributed maps of ground shaking, using interpolation procedures or information on ground motion spatial correlation. | |
| **Inputs** | **Outputs** |
| Ground motion recordings; Seismic station locations | Ground motion amplitude estimates |
| **Relevant algorithms and references** | |
| FinDER (Böse et al., 2012, 2018), in the USA, Switzerland, Chile, Costa Rica, El Salvador and Nicaragua; and ElarmS (Allen et al., 2009a), in the USA, Chile and Israel. | |

3) Estimation of ground shaking from initial characteristics of multiple seismic waveforms (Table 13).

*Table 13: Estimating ground shaking from initial characteristics of multiple seismic waveforms*

| **Description of Method** | |
|---|---|
| A first image of the seismic wavefield is obtained from the initial seismic waveforms recorded, using interpolation (e.g., data assimilation) techniques. This image is input to a physics-based wave propagation model to forecast final ground motion amplitudes. | |
| **Inputs** | **Outputs** |
| Spatially distributed seismic waveforms; Remaining parameters of the wave propagation model (e.g. Green's functions) | Ground motion amplitude estimates |
| **Relevant algorithms and references** | |
| PLUM (Hoshiba and Aoki, 2015; Kodera et al., 2016, 2018), in Japan | |

<u>Ground shaking estimation in On-site EEW systems</u>.

On-site systems traditionally compute rapid PGV estimates, using only the information from P-waves recorded at a single seismic station (Table 14). Similar to the estimation of earthquake source parameters, the estimates of ground shaking in On-site systems are less accurate as only one station provides seismic data.

*Table 14: Estimating ground shaking from initial characteristics of a single seismic waveform*

| **Description of Method** | |
|---|---|
| PGV is estimated from the amplitude (e.g., peak displacement) of the initial few seconds of the incoming P-wave train, using empirical relationships. | |
| **Inputs** | **Outputs** |
| Initial seismic waveform | PGV estimate |
| **Relevant algorithms and references** | |
| Onsite (Böse et al., 2009), in the USA; PRESTo$^{PLUS}$ (Colombelli et al., 2015; Zollo et al., 2010, 2014a), in Italy; and the EEW System for Southern Iberia (Carranza et al., 2013), in Spain | |

Computation of uncertainties.

Most of the algorithms listed in this section (e.g., PRESTo, G-FAST, OnSite, and EDAS-MAS) contemplate the uncertainty by considering a confidence interval on the estimate with width equivalent to two standard deviations of the empirical relationships adopted to compute ground shaking, assuming modal values for the source-related variables. On the other hand, Virtual Seismologist accounts for the complete lognormal PDF of ground shaking from the relevant attenuation relationship, incorporating the uncertainties quantified in Chapters 2.3.1 and 2.3.2.

### 2.3.4 Decision module for alert notification

Four different state-of-art criterions are currently used to decide whether or not triggering an alert:

1) Decision module to trigger alerts based only on the estimated magnitude of the event (Table 15).

*Table 15: Triggering alerts based on magnitude*

| **Description of Method** | |
|---|---|
| A warning is triggered if the magnitude estimate exceeds a certain threshold. The estimates are compared to magnitude bins previously computed that relate the magnitude to the potential damage that the earthquake might induce in each region of interest. | |
| **Inputs** | **Outputs** |
| Magnitude estimate | Warning trigger (yes/no) |
| **Relevant algorithms and references** | |
| SASMEX (Cuéllar et al., 2017; Suarez et al., 2009), in Mexico; KEEWS (Sheen et al., 2014, 2017), in South Korea; and the Beijing EEW system (Peng et al., 2011, 2013) in China | |

2) Decision module to trigger alerts based on the estimated magnitude and epicentral distance (Table 16).

*Table 16: Triggering alerts based on magnitude and epicentral distance*

| **Description of Method** | |
|---|---|
| Epicentral distances to target sites of interest are first computed based on earthquake location estimates. The magnitude and distance estimates are compared with magnitude-epicentral distance maps of predicted damage; if they lie within the portion of the map where damage is predicted, a warning is triggered. | |
| **Inputs** | **Outputs** |
| Magnitude estimate; Location estimate | Warning trigger (yes/no) |
| **Relevant algorithms and references** | |
| UrEDAS (Nakamura, 1988; Nakamura and Saita, 2007), in Japan | |

3) Decision module to trigger alerts based on ground motion amplitude (Table 17).

*Table 17: Triggering alerts based on ground motion amplitude*

| **Description of Method** | |
|---|---|
| A warning is released if the estimated values of ground motion amplitude (e.g., PGA or cumulative absolute velocity) exceed a damaging critical threshold | |
| **Inputs** | **Outputs** |
| Ground motion amplitude estimate (e.g. PGA) | Warning trigger (yes/no) |
| **Relevant algorithms and references** | |
| OnSite (Böse et al., 2009), in the USA; PRESTo (Satriano et al., 2011a), in Italy; Virtual Seismologist (Cua, 2005; Cua and Heaton, 2007) in the USA and Switzerland; Compact UrEDAS (Nakamura, 2004, 2008; Nakamura and Saita, 2007), in Japan; and IEEWS (Alcik et al., 2009; Erdik et al., 2003; Oth et al., 2010), in Turkey | |

4) Decision module to trigger alerts based on calculated seismic intensity (Table 18). Seismic intensity represents the most common decision variable among the methods included in this section.

*Table 18: Triggering alerts based on calculated seismic intensity*

<table>
<tr><td colspan="2"><b>Description of Method</b></td></tr>
<tr><td colspan="2">Seismic intensity is calculated from characteristics of the event waveform (e.g., peak ground motion amplitude) observed at seismic stations, using empirical equations. Warnings are triggered in a region if the estimated seismic intensity exceeds a certain value on the corresponding seismic intensity scale.</td></tr>
<tr><td><b>Inputs</b></td><td><b>Outputs</b></td></tr>
<tr><td>Ground motion/seismic waveform information (e.g. PGV)</td><td>Seismic intensity estimate; Warning trigger (yes/no)</td></tr>
<tr><td colspan="2"><b>Relevant algorithms and references</b></td></tr>
<tr><td colspan="2">ElarmS (Allen et al., 2009a; Allen and Melgar, 2019; Elizabeth Cochran et al., 2018; Ruhl et al., 2019; Wald et al., 1999; Wurman et al., 2007), in the USA; PRESTo$^{PLUS}$ (Colombelli et al., 2012a, 2013; Picozzi et al., 2015b; Zollo et al., 2010, 2014a), in Italy; JMA and PLUM (Hoshiba et al., 2008; Kamigaichi, 2004; Kubo et al., 2011; Liu and Yamada, 2014), in Japan; eBEAR (Chen et al., 2015), in Taiwan; and REWS (Böse et al., 2007), in Rumania.</td></tr>
</table>

The idea of implementing decision modules based on losses and damage has also been proposed by different authors. Examples include multi-criteria decision making approaches to select a trigger threshold for probable damaged bridges (Le Guenan et al., 2016), alerts based on losses quantified as casualties due to people trapped in elevators (Wu et al., 2016), and the performance-based EEW (PBEEW) approach (Iervolino, 2011; Iervolino et al., 2006, 2007a).

## 2.4 Limitations of the current EEW State-of-the-art algorithms

Considering the algorithms and methodologies introduced in Chapter 2.3 of this report, it is noticeable that currently EEW systems release warnings without considering damage/loss/harm metrics (Cremen and Galasso, 2020), rather the thresholds are calibrated in terms of estimated earthquake source parameters and/or ground shaking. Therefore, the warnings are triggered relying mainly on engineering judgment and not on explicit damage/loss analysis. This represents a substantial limitation, totally associated with decision-making procedures (e.g., activation of automatic procedures), that can be divided in three components:

- The general assumption that a given level of ground shaking will result in a specific level of damage. Regional EEW systems that release warnings based on estimations of ground shaking do not account for varying levels of structural fragilities across the affected area. It has been shown that damage probability and severity for a given level of ground motion considerable fluctuate across different types of structure/infrastructure/systems. In addition, it has been highlighted that the relationship between ground shaking and damage at a target site is highly uncertain (Cremen and Baker, 2019). Finally, failure to account for the uncertainties just mentioned tends to increase the potential of releasing false and missed alarms (Cremen and Galasso, 2020).

- Lack of losses metrics in the decision-making procedure. Accounting for losses is an important variable for decision-making, as decision-makers are more interested in measuring the value of an alert based on its ability to assure business continuity, rather than just being aware of the probable cost of physical damage to the site (Cremen and Galasso, 2020). This idea has also been introduced by Moehle and Deierlein (2004), ‘providing results in terms of economic losses, casualties and downtime, is more meaningful for decision makers and stakeholder groups, rather than structural damage in terms of an Engineering Demand Parameter (EDP)’.

- The alerts released by the system in terms of engineering parameters are difficult for the public to understand (Allen and Melgar, 2019; Velazquez et al., 2020). Confusing alerts make the public less likely to take preventative action (Goltz, 2002), which contrasts the actual function of the warning. To maximise the benefits of EEW alerts, they should contain robust messages (Cochran and Husker, 2019), which is best achieved using risk-orientated decision metrics (Cremen and Galasso, 2020).

## 2.5 Recent development in engineering applications of EEW.

As mentioned in chapter 1, and as it can be seen in chapter 2.3, the research regarding EEW has been the main goal for seismologists since the concept was formulated. Nevertheless, potential applications of these systems can be designed for real-time seismic mitigation and risk management or different critical structures and infrastructures.

The most reasonable measures seem to be automated safety procedures rather than triggering alert to the population, as sometimes warning times are not enough for individuals to carry out protection actions (‘drop, cover, and hold-on’ or move to a safer location).

Few are the designed applications available in the literature. This chapter provides a brief summary of some of the methodologies proposed by different authors, their main goals and the results achieved.

### 2.5.1 Control of Elevators in tall buildings

Automatically stopping elevators in high-rise buildings is one of the applications that have been designed to perform emergency response actions.

This methodology has been applied by Kubo et al. (2011) on a 29-stories high-rise building located in the Shinjunku campus of Kogakuin University, in Tokyo (Figure 4). Through a Real-time Strong-motion Monitoring System (RSMS), P-waves and S- waves arrival times are detected and the expected JMA intensity is estimated (chapter 3.5.3). Then, using a simplistic lumped mass model of the building (Kubo et al., 2008), displacement and acceleration demands for each floor of the structure can be obtained. For this particular building, a threshold of 2.1 cm in the displacement response of the building is defined, therefore, an alarm would be provided, and elevators would be stopped at the nearest floor, if this critical value is exceeded.

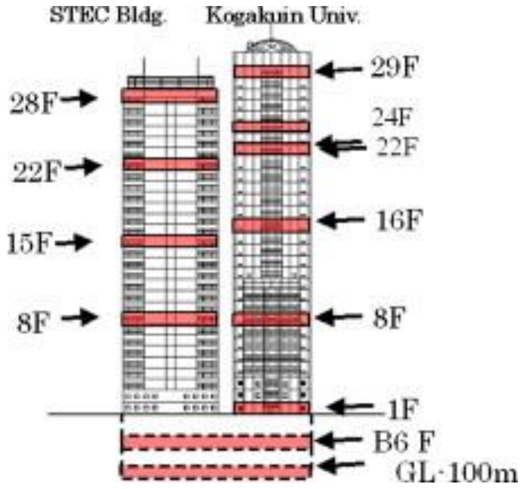

*Figure 4. Schematic representation of the 29-stories structure (Adapted from Kubo et al. 2011).*

Cheng et al. (2014) follow in general the same principle previously described, but differently, the method is based on a Performance-based Earthquake Early Warning (PBEEW) approach. The study is carried out for 29 different buildings located in the State of California, where a seismic sensing device must be installed in any single elevator, according to the state law. Considering the PBEEW framework, once the EEW system provides estimates of the earthquake source parameters, the first step is to calculate intensity expected demands (PGA) by applying existing Ground Motion Prediction Equations (e.g., Boore and Atkinson 2008). Then, the response of the building of interest is assessed by adopting a simplified structural continuum model proposed by Miranda & Taghavi (2005). Different warning messages are triggered by the system and elevators are stopped immediately at the nearest floor if the mean value of Peak Floor Acceleration (PFA) exceeds a critical value of PFA previously defined (Table 19).

*Table 19. Human comfort level to acceleration. Adapted from Cheng et al. 2014.*

| **Peak acceleration** | **Comfort level** | **Early warning message** |
|---|---|---|
| <0.5% *g* | Not perceptible | No shaking |
| 0.5–1.5% *g* | Threshold of perceptible | Minor shaking |
| 1.5–5% *g* | Annoying | Moderate shaking |
| >5% *g* | Very annoying | Strong shaking |

### 2.5.2 Real-time Assessment of train railways

Esposito & Emolo (2014) proposed a feasibility study for the real-time assessment of the Circumvesuviana Napoli Railway, based on a classical PBEE approach.

The Napoli Railway is composed of six lines which provide transportation to about 38 million passengers. Among the six branches, special interest is given to the Napoli-Baiano line, due to its proximity to the active fault system where the epicentre of the 1980 $M_w$ 6.9 Campania-Lucania Earthquake was located.

Damages induced by earthquakes in Railway Systems include examples such as, the stoppage of operations on a fraction of the system, permanent ground/railways deformations produced by fault displacements, ground failure effects, derailment of trains due to the ground acceleration. Within the Circumvesuviana network, the elements of the system that are more vulnerable to earthquake forces are: Viaducts, embankments and tracks. Viaducts are mainly damaged by permanent ground deformations, embankments by acceleration and velocity of the tremor, and tracks by ground failure effects such as liquefaction or falling of rocks. Line number six is deployed minimally on ground and the majority of its structure is settled on viaducts.

The larger sources of losses in a railway system can be listed as follows: derailment of trains, collision of incoming trains, and falling of trains from significant heights. Therefore, alarms thresholds for this section of the system were calibrated considering two actions if an alarm is triggered: Stop trains and carry out a deep and careful inspection of the railway or reducing the velocity of the trains and perform a fast inspection of the railways.

For earthquakes with $M_w < 5.5$, the impact on triggering false alarms is investigated. It is concluded that, in terms of induced losses due to the action taken, false alarms represent minimum losses in comparison with the benefits of triggering alarms. In addition, considering that passengers in the area expect occasional delays up to one hour every two years, delayed trains by one hour, due to a false alarm, might not represent a considerable impact. On the other hand, for earthquakes $M_w > 5.5$, users of the network might understand long inspection times as the damage in the system can be quite high (even if a false alarm is triggered).

### 2.5.3 EEW Systems for seismic mitigation purposes in Nuclear power plants

The International Atomic Energy Agency (IAEA) defines automatic SCRAM trip systems procedures (ASTS) as a potential seismic mitigation strategy against earthquakes (IAEA, 2011). ASTS seismic mitigation efforts related to EEW include actions such as: shutdown of reactors, turbines or generators systems, evacuation of the premises, fast access to fire-station tools, etcetera.

According to Cauzzi et al. (2016), shutting down a reactor is a delicate procedure that requires long time to be performed, during which many pieces of the system will be operational and some not, including safety systems. Therefore, if the shutting down is performed during a seismic event, the vulnerability level will be considerable higher than the one that would be expected under normal full operations (Figure 5). This concept leads to the idea that shutting down a power plant due to seismic forces is a mitigation action that has to be performed before the arrival of shaking waves to the site of interest, which leads to the main concept of EEW.

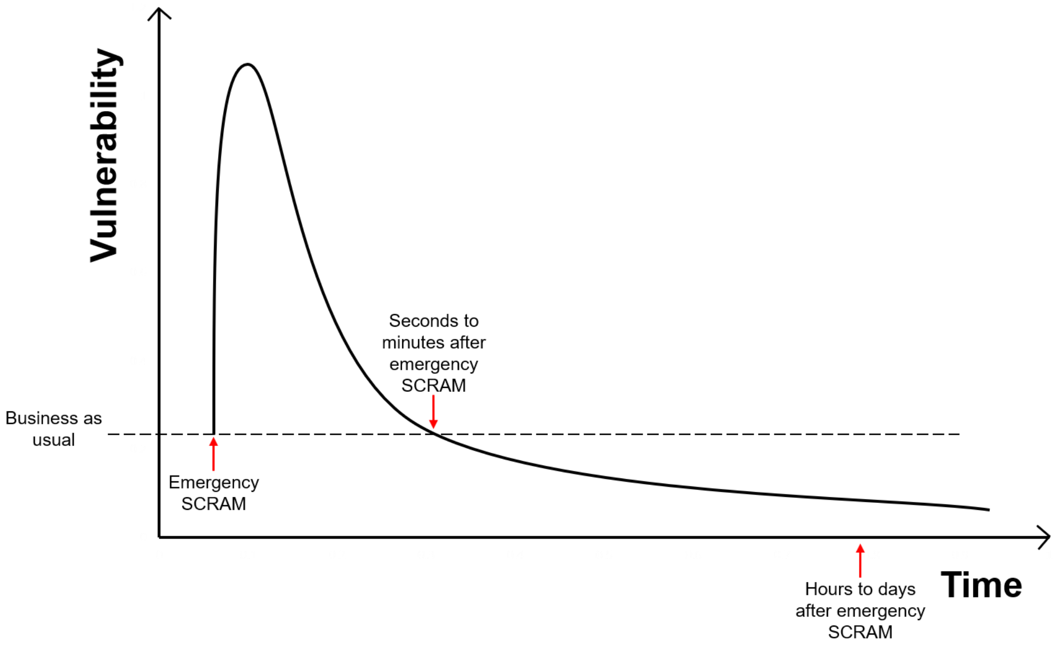

*Figure 5. Vulnerability of a nuclear reactor following SCRAM. Adapted from Cauzzi et al. 2016.*

The decision-making process that defines whether to trigger an alarm or not for power plants may be defined considering a benefit-cost ratio, where an action with cost (C) would prevent losses (L), with a likelihood of occurrence (P) (Woo, 2013).

The Swiss Seismological Service and the French Geological Survey, studied the feasibility of implementing EEW on Nuclear Power Plants (Cauzzi et al., 2016). Based on the cost-benefit approach previously defined, four Nuclear Power Plants operating by Swissnuclear[3] were tested by considering a historical earthquake catalogue of Switzerland. Earthquake demands provided by the EEW system were obtained by implementing the Virtual Seismologist approach (Cua and Heaton, 2007). The study concludes that EEW systems might be a potential tool for the protection of power plants, but triggering unnecessary false alarms is a very important issue that has to be properly studied. Cauzzi et al. (2016) shows that triggering a false alarm in Switzerland represents: 1) the reduction of the reactor's lifetime, 2) economic losses from power sales, 3) time issues for the application to restart the plant, and 4) high costs for repowering up. In monetary terms, the losses related to no sales is,

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[3] https://www.swissnuclear.ch/en/home.html

for Switzerland, USD 1 million every day, and the application’s cost to restart the plant is worth USD 250 million per SCRAM.

An actual implementation of EEW for the protection of a Nuclear Power Plant in Lithuania is introduced by Wieland et al. (2000). Based on an on-site system, the network consists of six seismic stations (each with a three stations subsystem) surrounding the power plant, with a plant-station and station-station distance of 30 km. In addition, a seventh station is installed in the main body of the power plant, in case the epicentre of the earthquake is within the protected 30 km radius. To prevent the core of the reactors from meltdown, two seconds are enough to perform the protection actions. Considering that an earthquake occurs outside the seismic fence protecting the plant, and that the velocity of S- waves is 3.5 – 4 km/s on average, a warning of 8.5s can be provided, which is much more than the time required to isolate the reactors. An alarm ‘vote’ is considered when one of the stations record accelerations larger than 0.025g. Once 2 of the 3 substations have provided a vote, the seismic alarm is declared positive, and the reactors are shut down.

### 2.5.4 EEW for the protection of natural gas networks

As described by Zulfikar (2014), the Natural Gas Network of Istanbul has developed an approach that aims at preventing economic and human losses triggered by natural gas disasters due to earthquakes (e.g., fires due to broken pipelines and gas leakage). One of the goals of the project is the use of the Istanbul EEW system for the protection of the natural gas system of Istanbul.

Designed as on-site system, and considering that short warning alerts are available, the unique but effective mitigation action that can be adopted in the network is the automatic shut-off of gas flow. The automatic shut-down is implemented if pre-defined threshold values in term of PGA or PGV are exceeded. In addition, damage maps of the affected areas of the network are instantly drawn and can be rapidly detected, so special engineering teams are sent to check and fix the possible affectations, reducing the risk of future non-desired consequences.

### 2.5.5 Integration of structural control and EEW

Changing the dynamic properties of buildings (e.g., damping and/or stiffness) using isolators or dampers is an attractive seismic mitigation for the reduction of vulnerability and damages in these structures. Passive and semi-active strategies combined with EEW have been designed to accomplish the reduction of induced vibrations to buildings before the arrival of the oncoming tremor. Chapter 2.5.5 summarises the studies done so far in this matter.

Seismic isolation using air bearings.

Fujita et al. (2011) studied the implementation of air bearings as an isolation device for structures. By using this methodology, a thin air film is produced between the ground and the structure, isolating the building on a flat surface separated from any induced vibration coming from the ground (Figure 6). The activation of the floating mechanism can be triggered by any wind load, or small load, therefore, the system requires specific earthquake information, so it is not activated in wrong conditions. The information relevant of an earthquake is obtained by EEW (i.e., the EEW system managed by the JMA, chapter 3.5.3). According to the information provided by the system, the algorithm decides whether the building has to float or not. If the oncoming ground shaking activates the floating mechanism, the building would keep floating until the event is over. Once the earthquake has finished, the mechanism is off and the structure lands back on its original position. In the worse-case scenario of malfunctioning of the floating mechanism, the air bearings function as friction bearing pads, absorbing some of the seismic waves.

The validation of this methodology is carried out on an isolated carbon steel frame with weight equal to 636kg. Four air bearing are located on all the corners of the frame, each with a bearing capacity of 235 kg. Sinusoidal waves are induced to the system on a shaking table during 16s with variated frequency between 1-10 HZ. The result of the test proves that the air bearings reduced the acceleration demand on the structure, leading to a positive isolation outcome. However, as the author mentions, adopting this methodology presents the following disadvantages:

- The acceleration on the system is reduced significantly, nevertheless, the horizontal displacement generated during the flotation is considerable large. Considering a real structure, this effect could promote pounding events during a seismic event.
- The system is complicated in assembling and operation in comparison with conventional isolation systems. In addition, the size of the components of the systems requires considerable space.
- In case of an electric cut, which is high likely during large earthquakes, the air compressor would not work, avoiding the full operation of the air bearings.

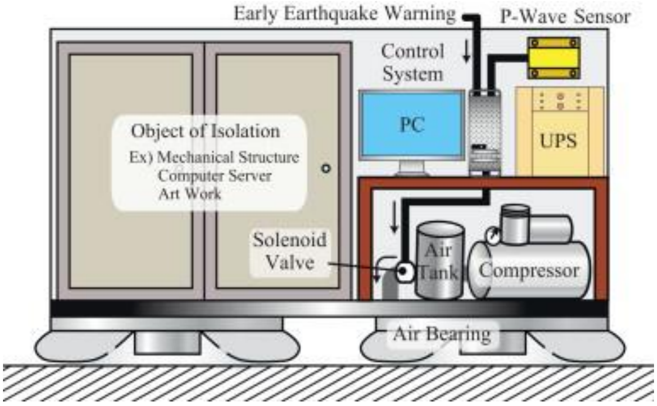

*Figure 6. Air bearing isolation system. Adapted from* Fujita et al. 2011.

Semi-active independently Variable Dampers and EEW.

De Iuliis and Faella (2013) developed a strategy to combine semi-active structural control with EEW. By calculating the frequency content of the recorded acceleration histogram at every station of any network, semi-active independently variable dampers (SAIVD) are activated adding damping and stiffness forces to the protected structure. The SAIVD, developed by Nagarajaiah and Narasimhan (2006), is composed by four linear visco-elastic spring-dashpot elements positioned in a rhombus configuration (Figure 7). The forces generated on the damper depend on the real-time variation of angle of the spring-dashpot elements or the aspect ratio of the rhombus configuration. This variation of angles is performed by a mechanical actuator that is calibrated to be activated according to the estimates of the EEW System.

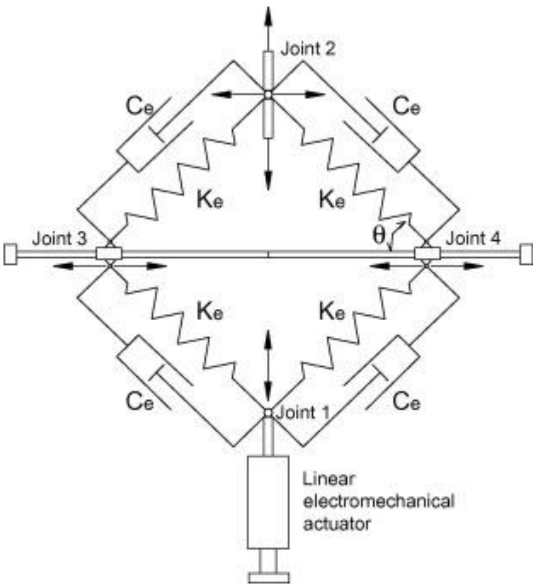

*Figure 7. Analytical model of the variable stiffness/damping device. Adapted from De Iuliis and Faella 2013.*

The device is tested on an isolated five degree of freedom system proposed by Johnson et al. (1998), that has been studied previously for the application of different structural control strategies. This structure is a lumped parameter model considered to have minimum effects given nonlinearities on the system dynamics. The effectiveness of the proposed methodology is tested by considering two sets of recorded ground motions: a set of earthquakes with signals with high energetic content unfavourable for isolated structures, and one set of unscaled records from Europe. Simulating an EEW procedure, for each event the Fast Fourier Transform of the acceleration signal of the oncoming earthquake is computed, obtaining the frequency content of the event. This information is used to estimate the seismic demand of the building, and accordingly the SAIVD is activated to add the required damping and stiffness to the structure. The overall results of the system reveal significant reduction of Drift Ratios on the structure, reducing the risk of global collapse. However, Peak Floor Accelerations showed to be significantly amplified in the superstructure (in the order of 1.6 compared to the results obtained with the uncontrolled structure), increasing the possibility of damage on non-structural elements.

The fact of considering linear behaviours on the performance of the SAIVD and the response of the structure might represent a conservative approach for the test of isolation systems attached to structures. The demands obtained after the analysis may not represent accurately the predictions in terms of structural response and the dampers could be activated (or not) when it is not necessary.

#### Variable Viscous Dampers and EEW

Iervolino et al. (2010) tested a single degree of freedom system considering braces equipped with variable viscous dampers, as semi-active links. The devices, for comparison reasons, are set on ‘passive on’ and controlled modes, as explained in chapter 4.

Incremental Dynamic Analyses (IDA) were performed on the aforementioned structure, considering 21 European ground motion records, scaled from 0.1 g to 1 g, to obtain the probabilistic relationships between IMs and EDPs. The EDPs considered to assess the damage in the structure are Interstorey Drift Ratio (IDR) and PFA.

This study concluded and proved, that the drift and the peak acceleration at the top floor of the structure may be reduced if EEW triggers structural control conditioned to the results given by Real Time Probabilistic Seismic Hazard Analysis (RTPSHA; explained in chapter 4).

### 2.5.5.4 Magnetorheological dampers and EEW

Maddaloni et al. (2013) , investigated the seismic response of a bridge located in Orange County, California (Figure 8), equipped with MR dampers (fully described in chapter 4).

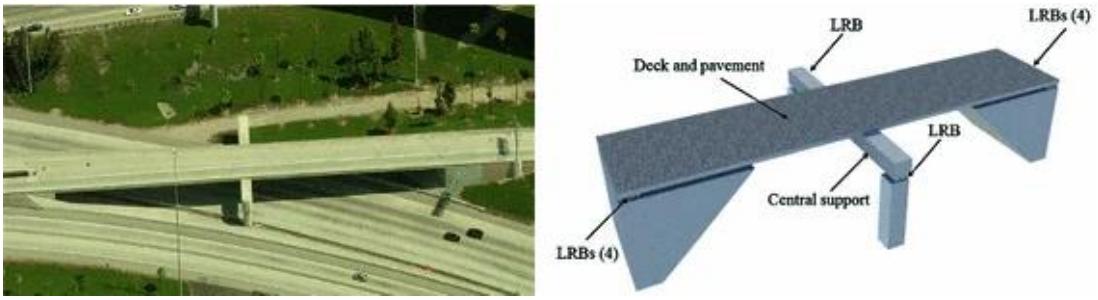

*Figure 8. Benchmark highway bridge located in California. Adapted from Maddaloni et al. 2013.*

The study describes the methodology followed to design a calibrating algorithm of MR dampers given the information provided by EEW, aiming for the seismic protection of the bridge. The algorithm was calibrated by running non-linear time history analyses feeding the MR dampers with a different value of voltage, ranging from 0 to 10 V with a step of 25mV. The response of the structure was assessed considering three different EDP (peak base shear, peak base moment and peak mid-span displacement). For each EDP, a diagram correlating the value of voltage correspondent to that EDP was drawn and for each diagram the optimal value of voltage leading to the minimum value of EDP was found. The optimal voltage and the spectral acceleration ( $S_a(t_1)$ ) representative of each earthquake were plotted and through a trial and error procedure, a hyperbolic tangent function was obtained. This function was the algorithm defining the optimal value of voltage that had to be applied to the MR damper in order to get the optimal response of the structure.

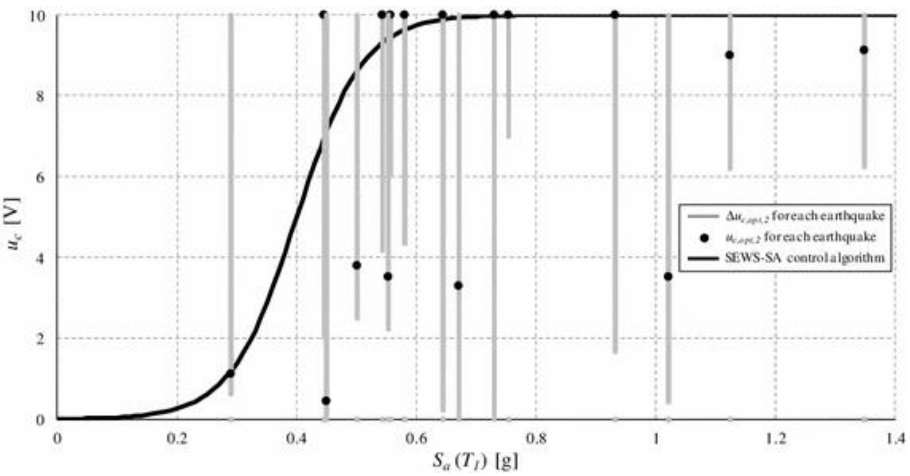

*Figure 9. Control algorithm for MR Dampers. Adapted from Maddaloni et al. 2013.*

Once the algorithm was defined, the effectiveness of the proposed system was compared with active, passive and semi-active control methodologies for seismic protection of the bridge. The evaluation was carried out by performing Non-linear Time History Analyses taking into consideration 16 ground motions, with moment magnitudes ranging from 5.75 to 7.62.

This study concluded that the proposed system represents the best option for seismic protection of the bridge among all the techniques tested. Nevertheless, few limitations can be identified in this study:

It is concluded that the uncertainties involved with the PGA estimates provided by the EEW system do not propagate to the seismic response of the structure. Following the methodology proposed by Iervolino et al. (2009), the dominating uncertainty in the real-time hazard analysis is that of the ground motion prediction equation. Thus, this uncertainty is still involved in the prediction of structural response. Therefore, the uncertainties in the prediction of PGA cannot be neglected as their impact in structural response is considerable.

The optimal control algorithm of the MR dampers was designed by contemplating a single EDP. The designed algorithm should provide the optimal value of the voltage that would provide the optimal structural response considering a combination of the EDPs of interest (i.e., optimal peak base shear, peak base moment and peak mid-span displacement responses, simultaneously). Given that various EDPs have different measure units/variables, alternative methodologies (i.e., losses) must be used to provide a final algorithm able to incorporate the representative contribution of all the EDP's taken into consideration.

## 2.6 Limitations of the current engineering applications of EEW

As mentioned in Chapter 2.4, current practice for EEW is to activate mitigation actions when a given IM (e.g., PGA) exceeds a pre-defined IM critical threshold. For building-specific applications, this also represents a limitation as mitigation actions such as shutting down a power plant (Wieland et al., 2000) or closing gas pipelines (Zulfikar, 2014) require to be activated in more certain scenarios. An attractive idea proposed in this thesis is to evolve the classic approach based on just one IM, to a framework that involves the combination of two or more Engineering Demand Parameters (e.g., IDR and PFA), that can effectively provide a better assessment of a structure/infrastructure during an earthquake. Furthermore, the approach introduced in this thesis is updated for application 1 (Chapter 4) in which the EDPs are computed in terms of losses (i.e., monetary costs). This strategy allows for the recognition of the most favourable performance of a structure in terms of two (or more) combined EDPs, different to other studies where the assessment is carried out by singular EDPs (e.g., Maddaloni et al. 2013).

Some of the applications introduced in Chapter 2.5, control of elevators in tall buildings, for example, do set thresholds in terms of an EDP (i.e., PFA). However, the evaluation of EDPs still depends on the computed values of PGA. This is also a significant limitation as it has been shown that PGA might not be the best variable of choice as tall buildings are more sensible to long-period acceleration (short frequency) and PGA is controlled by high-frequency components of the ground motion (Malhotra, 2006). The approach proposed for application 2 (Chapter 5), based on the computation of EDPs, represents a more efficient methodology as EDPs are directly conditioned on the earthquake source parameters estimated by an EEW.

# Chapter 3. Beyond the technical components of EEW: socio-organisational aspects

## 3.1 Introduction and motivations

In recent decades, there has been an increased tendency in the literature to investigate both the technical and the social-science-related aspects of disaster prevention/mitigation, preparedness, response, and recovery. Events such as the 2004 Indian Ocean earthquake and tsunami, and the 2011 Tohoku (Japan) earthquake, tsunami, and nuclear meltdown, have raised awareness about the various domains/disciplines involved in risk forecasting/management strategies and the need to develop holistic approaches to early warning methods at a broader scale. According to the definition proposed by United Nation's Office for Disaster Risk Reduction (UNDRR), early warning systems can be defined as "An integrated system of hazard monitoring, forecasting, disaster risk assessment, communication and preparedness activities, that enable individuals, communities, governments, businesses and others, to take timely action to reduce disaster risks in advance of hazardous events" (UNDRR, Terminology updated February 2017)[4]. The official definition also differentiates between early warning systems and multi-hazard early warning systems, suggesting the creation (where possible) of new platforms that could address several hazards and/or their impacts, increasing efficiency and coordination (UNISDR, 2017).

The topic of early warnings has acquired considerably more interest also in practice, which is reflected in various policies and international guidelines. In 2015, the member states of the United Nations endorsed the *Sendai Framework for Disaster Risk Reduction* (UNISDR, 2015), where it is specified that early warning must be a priority and early warning systems have to be substantially evolved by 2030 (UNISDR, 2015). Early warning systems can also play a crucial role in mitigating highly complex events, such as cascading and interacting hazards and risks (Pescaroli et al., 2018). In

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[4] https://www.preventionweb.net

particular, Pescaroli and Alexander (2018) suggested that researchers should better integrate the technical components of early warning with practices of organisational resilience, for supporting the management of decisional uncertainties. Common training with these systems, including simulation exercises/drills, are also essential.

This chapter specifically focus on earthquake early warning (EEW) systems. These systems combine real-time seismic instruments, fast telemetry capability, data processing software and methodologies/models/algorithms that can 1) provide real-time seismic-source information (e.g., rupture location and magnitude) and/or the ground-shaking intensity of ongoing earthquakes in the early stage of fault rupture; and 2) issue (based on some decisional rule) real-time warnings to the public or other end users in large urbanised areas before they experience the strong shaking that might cause damage/loss. The warning triggered by an EEW system can be considered a tool to improve emergency preparedness/rapid response and ultimately to minimise economic and human losses during earthquakes (e.g., Heaton, 1985; Strauss and Allen, 2016; Wieland, 2001). In the specific case of EEW, even recent review studies, such as the one by Allen and Melgar (2019), tend to focus on the technical aspects of EEW systems, without providing a full and systematic description of the multi- and cross-disciplinary challenges associated with EEW operation. Herein, cross-disciplinarity is considered as the fact of addressing one discipline from the perspective of another, without crossing techniques or ideas. On the other hand, multi-disciplinarity is defined as the combination of two or more disciplines working together, each contributing from their disciplinary knowledge[5].

Implementation of EEW systems should always consider local specificities, for instance in terms of risk perceptions at both individual and community levels, governance and institutional arrangements (Twigg, 2003). New EEW methodologies (and their practical implementations) require a process of outreach and capacity building that should go beyond the seismology (and

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[5] https://link.springer.com/referenceworkentry/10.1007%2F978-1-4419-1428-6_1476

engineering) community (Allen et al., 2009b). EEW failures are not just technical in nature, such as missed or false alarms, but may be due to organisational weaknesses at the institutional level, i.e., lack of response training to end users/community by official bodies, such as civil protection. According to Herovic et al. (2019), there are still open questions on how societal drivers (such as the understanding of local culture and organisational needs), interact with both technological choices (such as decision support platforms and uncertainty modelling/communication) and information delivery (practices and policies needed for action). A better understanding on how decisional uncertainties in the warning process could influence preparedness or mitigation strategies, for example, in terms of differences in the available lead time and expected ground shaking in specific regions, is urgently needed (Wald, 2020).

This chapter aims to develop a state-of-the-art review of both technical (seismology and engineering) and socio-organisational (social science, policy and management) components of EEW, in order to understand common gaps for research and practice. This chapter aims to address some key questions that have had limited examination previously, such as: 1) *What interactions, if any, exist between the technical and the socio-organisational components of EEW*? 2) *What improvements are required in the socio-organisational components to make EEW systems more effective*? 3) *What lessons can be learned from EEW systems implemented around the world*?

This review will focus in particular on case studies of Italy, United States' West Coast, Japan, and Mexico. The choice of these case studies will be explained in the methodology section, while the common lessons learned will be integrated with other evidence from worldwide cases in the discussion section. The conclusions will highlight directions for future research.

It is worth noting that throughout this chapter, “alert” and “warning” will be used as synonyms to indicate “an alarm signal or message coupled with a recommendation or order to take action such as mobilize or evacuate" (Alexander, 2002).

## 3.2 Beyond the technical components of EW systems

The first challenge of approaching EEW systems from a multi- and cross-disciplinary perspective is deciding which components to include in the review, and how they interact which each other. The *Third International Conference on Early Warning* held in 2006 (UNISDR, 2006) defined the overall conceptual framework of early warning systems, highlighting the need to integrate four inter-related elements in their development. Effective "end-to-end" and "people-centred" early warning systems should include: 1) disaster risk knowledge, based on the systematic collection and understanding of data on the dynamic interrelations of exposure, hazards, and vulnerabilities; 2) detection, monitoring, analysis and forecasting of the hazards and possible consequences; 3) dissemination and communication, by an official source, of authoritative, timely, accurate and actionable warnings and associated information on likelihood and resulting impact. Multiple channels must be identified and used to reach the exposed population/users, defining simple messages and useful information; and 4) preparedness at all levels to respond to the warnings received. This should include emergency planning and community awareness education. These four interrelated elements need to be coordinated within and across sectors/disciplines for an early warning system to work effectively and to include a feedback mechanism for continuous improvement. Failure in one element or a lack of cross-component coordination could lead to failure of the whole system.

Moreover, the document by UNSIDR (2006) pointed out some cross-cutting issues, including the need for effective governance and institutional arrangements to support the development and implementation of early warning systems (including the legal and regulatory frameworks), and the involvement of the local community to activate bottom-up strategies for vulnerability reduction (UNISDR, 2006). According to Lindell et al. (2007), an essential element of warnings is that the communication has to produce a response action, so the information must be received and understood. Therefore, the technical elements cannot be considered alone but strategic decisions must be made on how the dissemination process is developed, defining appropriate communication mechanisms (e.g., television broadcasts and social media) according to the time of the day, and which elements of local culture, risk perceptions and people behaviours can influence this process. Similarly, Smith and Petley (2009) highlighted that warnings are more useful when information on upcoming hazards is combined with advice on short-term actions, such as the activation of evacuation procedures (if the warning time allows).

Various authors have suggested that the implementation of the technical components of early warning systems may be inadequate on its own (e.g., Allen and Melgar, 2019; Basher, 2006; Kelman and Glantz, 2014; Quarantelli, 1984). A classic work by Quarantelli (1984) defined very clearly that the reactions to warning for imminent threats are generally driven by factors such as institutional development and type of dissemination (formal vs. informal), perceived relevance, content (specific vs general), proximity to the hazard, previous experience and validation (e.g., interactions with others). Effective early warning systems should not rely on a “top down” approach in which the emergency planning choices are imposed on the citizens; instead, these choices should be socially embedded. Patterns of inadequate engagement in the design and development of an early warning system could lead to a perceived lack of ownership, with consequent mistrust in the authorities/experts managing it and weaker political and economic support for further developments (Basher, 2006). Kelman and Glantz (2014) pointed out that the best approach to the design and implementation of an early warning system should be one where communities/end users are involved from the early phases of development rather than towards the end, in order to keep the technical tools oriented to their needs and specificities.

Describing specifically EEW systems, Allen and Melgar (2019) highlighted three main categories of users that need to be considered: a) individuals that undertake personal decisions and actions; b) automated response applications that need an institutional and company/organisation background on how to implement the process (e.g. automatic stop to railroads); and c) individuals and institutions/organisations that use the information for situational awareness. In each context, users are likely to behave differently, and some categories may be more prominent than others. It has also been highlighted that early warning systems need to integrate mechanisms to incorporate feedback and experience from users to improve the effectiveness of how a warning is translated into action (e.g., Allen and Melgar, 2019; Basher, 2006). Moreover, when dealing with utility services and infrastructure, early warning systems should be considered/integrated into new practices of organisational resilience, defined as “the ability of an organisation to anticipate, prepare for, and respond and adapt to incremental change and sudden disruptions in order to survive and prosper” (BS 65000:2014)[6].

## 3.3 Methodology

This chapter develops a “traditional or narrative literature review”, according to the methodological criteria proposed by King et al. (1994) and Cronin et al. (2008).

First, this chapter provides a brief overview of the technical components of EEW systems, on which most of the existing literature has concentrated, highlighting how they work, and the various challenges faced in EEW implementation. Secondly,  the literature centred on the socio-organisational components of EEW is explored, to understand how various related drivers can influence the effectiveness of the technical tools. This chapter conducts the review through an in-depth analysis of four case studies covered by most of the literature, and then discuss it with the support of other worldwide evidence available. The case studies selecteded represent different levels of

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[6] https://www.bsigroup.com/en-GB/about-bsi/media-centre/press-releases/2014/november/Organizational-resilience-standard-published/

advancement in the technical implementation of EEW systems, as explained by Allen and Melgar (2019):

- Italy, where EEW is technically advanced and subjected to real-time testing in the Campania region, but it is not open to the wider public;
- United States' West Coast, where EEW is disseminated publicly to a fraction of the population (i.e., California). Selected end users receive alerts in areas where warnings are not public, and the development of a full public system is still in progress;
- Japan and Mexico, which have the most developed public alert distribution systems that disseminate alerts via multiple channels. EEW is available nationwide in Japan and is well integrated in safety procedures and practices, such as those for critical infrastructure management. In Mexico, EEW remains more fragmented and less integrated holistically into organisational resilience.

It should be noted that the selection of documents involved a replicable process to assure the consistency of this work and the possibility of future updates (Berg, 2001). An in-depth screening of scholarly literature was undertaken using both Google Scholar[7] and Scopus[8], because the databases of the two research engines have different characteristics. Indeed, Google Scholar covers any document with a seemingly academic structure, including for example, conference proceedings, while Scopus comprises a database of documents–mainly journal papers-from approximately 5,000 publishers that have been selected by an independent committee.

The study implements a cross-reference approach between the identified documents to select additional publications of interest. A final check of gray documentation, such as policy reports, and open-source peer-reviewed papers/reports was performed on PreventionWeb[9], the knowledge platform for Disaster Risk Reduction of the United Nations.

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[7] https://scholar.google.com/intl/en/scholar/about.html
[8] https://www.elsevier.com/en-gb/solutions/scopus
[9] https://www.preventionweb.net

It was decided to focus the review primarily on literature published after 2004, i.e., in the period between 2005 and 2020, for the following reasons:

- Events, such as the 2004 Indian Ocean earthquake and tsunami, have significantly boosted the technical and non-technical development of early warning in general (and specifically EEW) since 2005;
- The technological evolution of society, associated with the widespread use of the internet, social media, and smartphones in the early 2000s, radically changed the components of disaster risk and the context of early warning systems, including EEW (Pescaroli and Alexander, 2018). This means that older papers will no longer contain valid concepts/lessons.

The key words used for the research were: “earthquake early warnings systems”, “social sciences and early warnings”, “organisational resilience”. The first round of documents was then selected by searching for non-technical words/phrases in the abstract or title, including: social component/driver/sphere; organisational component/driver/sphere; operational component/driver/sphere; political component/driver/sphere; cultural component/driver/sphere; community; lessons learned; framework; review; state-of-the-art. The results in Scopus reflected the predominant focus of the literature on the technical components of EEW systems. Most of the work –approximately 1,700 papers- was concentrated in engineering, earth and planetary sciences, and computer sciences. Research in the domains of social sciences, medicine, business and management, decision sciences, arts and humanities, psychology, and economics comprised a total of 175 papers in English. However, many of these documents were not relevant for this study, because, for example, they focused on generic early warning systems or their technical components. Thus, the abstracts were filtered again to determine which papers: a) were focused on the socio-organisational aspects of EEW worldwide, with a particular focus on reactions to warnings or integration in policies; and b) supported the description of the case studies of interest.

### 3.3.1 Considered domains

Each case study will be introduced by providing a general description of the local context and technical details of the EEW system implemented in the region. Then, relevant literature will be discussed with respect to different domains or spheres, i.e., operational, political and governance, social and behavioural, and organisational. Framing the discussion through the lens of the various spheres facilitates communication to a multidisciplinary audience. It is worth noting that some topics/findings can be seen as cross-cutting between different spheres, as discussed in the following sections; hence, the spheres should not be interpreted as rigid divisions.

#### Operational Sphere

This category includes tactical elements and tools that influence how EEW is developed and disseminated, such as social media/sirens, information on lead times (the time available before the arrival of the strong ground shaking at target sites) and expected impacts, including level of uncertainties in the predictions (when considered). In other words, the operational sphere includes what Alexander (2002) refers to as “the technological processes of conveying the message (i.e., communication systems)”.

#### Political and Governance Sphere

This category includes contents associated with political and legislative issues, such as the legal framework in which EEW systems are implemented/operate, or accountability for dissemination and strategic decision making.

#### Social and Behavioural Sphere

This category includes people’s knowledge/understanding, perception, and opinion on EEW systems. The sphere is closely linked to the local context in which EEW systems operate, including the local culture, existing trust in institutions, local knowledge and experience with the considered hazard, informal training, household preparedness, community networks and vulnerability factors such as resource distribution.

Organisational Sphere

This sphere refers to organisations, such as civil protection, public utilities, and enterprises, that incorporate actions associated with EEW. The aim is to understand the internal procedures of these organisations (if any) with respect to EEW, such as the activation of business continuity plans.

## 3.4 EEW systems: physical grounds, technical concepts, methods and perspectives

To avoid repletion and for brevity purposes, the reader must refer to chapter 2 of this report for an explanation of the technical components of EEW systems.

## 3.5 Case-studies analysis: Italy, US-West Coast, Japan, and Mexico

Four case studies have been considered for this state-of-the-art review: Italy, United States-West Coast, Japan, and Mexico (Figure 10). The technicalities of each system are explained and a description of the operational, political, socio-behavioural and organisational spheres is provided, as described in Considered Domains.

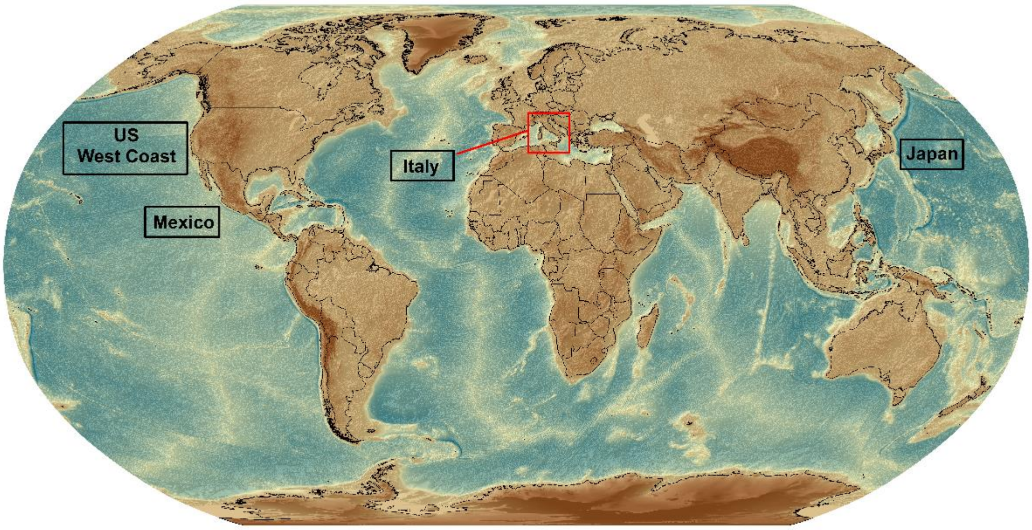

*Figure 10. Case-studies considered for the review: Italy, US-West Coast, Japan, and Mexico.*

### 3.5.1 Italy

The EEW system in Southern Italy has been implemented since 2005 due to the high seismicity in the Southern Apennine area directly affecting the Campania-Lucania region, where large urbanised cities, like Naples, are located. According to Zollo et al. (2014a), the system relies on the Irpinia Seismic Network (ISNet), which is formed of 31 seismic stations distributed in the Campania-Lucania region. The system is regional, and is based on a methodology that predicts the source parameters of the ongoing earthquake using various algorithms that are loaded into the main software platform called PRobabilistic and Evolutionary early warning SysTem (or PRESTo; Emolo et al., 2016).

PRESTo estimates the hypocentre location of an earthquake using the ‘RTLoc’ approach proposed by Satriano et al. (2008), which is based on the equal differential time formulation introduced in Regional Early Warning Systems. The magnitude of an earthquake is estimated by PRESTo according to the ‘RTMag’ algorithm proposed by Lancieri and Zollo (2008). With location and magnitude defined, GMMs for the Campania-Lucania region are implemented to estimate the expected values of PGA, PGV, and instrumental intensity (or even macroseismic intensity) at the sites of interest (Satriano et al., 2011a).

Several performance tests have been carried out on the system, using large and small historical earthquakes. If a dense seismic network is deployed around the fault region, PRESTo can provide reliable estimations of the location and magnitude of the event, as well as ground-motion intensities, within 5-6 seconds from the event origin time (Zollo et al., 2014a). In addition, Picozzi et al. (2015a) considered the whole of Italy in a feasibility study to explore the potential of implementing a nationwide EEW system based on the PRESTo framework. The authors explained that reliable messages about large earthquakes could be provided to the community with lead times of the order of 25 s in several urbanized areas. This means the alarm could reach hundreds of municipalities in enough time, and residents could be supported by related education and training on basic protective actions (e.g., Drop-Cover-Hold On). However, despite the advanced, state-of-the-art algorithms used in PRESTo, public warnings are still not fully operational in the Campania Region.

### Operational sphere

When PRESTo issues an alarm, this is shared to a list of recipients (mainly researchers) that have been selected as beta testers by the system developers. These recipients have access to estimated earthquake parameters registered at every station in the network, estimates of the location and magnitude of the earthquake as well as arrival time, estimates of PGA, PGV, and other IMs at target sites, and theoretical P- and S-wave propagation paths. Users can adjust the threshold for triggering a warning alarm, which is disseminated via the Internet and SMS (Satriano et al., 2011a).

### Political and governance sphere

At the political and governance levels, there have been preliminary attempts to publicly operate an EEW system in Campania. However, the Italian Department of Civil Protection has prioritised different earthquake risk mitigation actions above EEW, such as reduction of the vulnerability of critical infrastructures and improved public seismic risk awareness (Clinton et al., 2016). More attention has been given to tsunami warning systems in which seismic detection, location, and magnitude estimations are integrated together (Bernardi et al., 2015).

### Social and behavioural sphere

There is no specific study addressing the development of a holistic and bottom up EEW system in Italy with explicit focus on the general public. This research gap is particularly pertinent in the context of this case study, given that previous work has highlighted a strong need for improving training and information practices of (general) earthquake preparedness in Italy (e.g., Pescaroli et al., 2012).

### Organisational sphere

Literature on the organisational sphere is very limited for Italy. Esposito and Emolo (2014) carried out a study to address the feasibility of adopting the Campania EEW system for the Circumvesuviana Napoli railway system. Although the research was quite preliminary in nature, the authors conclude that there is potential for EEW to be applied to the railway system in the region, in line with evidence of other case studies such as California.

Different authors have addressed the possibility of equipping existing seismic networks/stations with EEW capabilities for the entire Campania region. Emolo et al. (2016) presented a region-wide (Campania) case study that focused on public schools. The study finds that 3-5 s are enough for well-trained students to find shelter and protect themselves before the arrival of earthquakes. The authors ultimately conclude that implementing EEW systems for schools in the examined region would be effective, given that the largest concentration of residents in Campania is located in coastal areas away from where the most damaging earthquakes occur along the Apennine chain. The aforementioned work was motivated by a smaller case study presented by Picozzi et al. (2015b), in which the EEW system of the Campania Region was tested in a specific school located in the Irpinia region. For this very particular case, it was shown that alerts can be provided to occupants of the school 13 s before the arrival of strong shaking in line with the historic M 6.9 1980 Irpinia event.

### 3.5.2 US – West Coast

A prototype regional EEW system for California was proposed by Allen and Kanamori (2003) as a mitigation strategy to reduce potential impacts from earthquakes in the region of Southern California. The practical implementation of the system was initiated in 2007, funded mainly by the United States Geological Survey (USGS) and the following academic institutions: the California Institute of Technology (Caltech); the University of California, Berkeley (UC Berkeley); the University of Washington; the University of Oregon; the University of Southern California; and the Swiss Federal Institute of Technology (Böse et al., 2014; Kohler et al., 2018). The system, named CISN ShakeAlert, makes use of the existing California Integrated Seismic Network (CISN) that includes approximately 380 broadband and strong-motion stations across California. The stations detect ground motions coming from the high-potential seismic regions nearby, such as the San Andreas Fault, the Hayward Fault and the Cascadia subduction zone (Calkins and Lieberman, 2014; Given et al., 2018; Johnson et al., 2016; Strauss and Allen, 2016). The production prototype (v1.0) of ShakeAlert was established for California in early 2016 (Kohler et al., 2018). A newer version (v1.2) was established in 2017 for the West Coast states of Washington, Oregon and California and provided earthquake notifications that were distributed to a group of local beta users.

The system was originally equipped with three different EEW algorithms (Böse et al., 2009; Chung et al., 2019) that worked simultaneously in order to estimate earthquake source parameters: 1) Onsite (Wu and Kanamori, 2005); 2) ElarmS (Allen et al., 2009a); and 3) Virtual Seismologist (Cua and Heaton, 2007).

In 2017, an evaluation of the ElarmS and Onsite algorithms resulted in a single unified point-source algorithm known as EPIC (Earthquake Point-source Integrated Code) that is primarily based on the most updated version of ElarmS, ElarmS-3 (E3) (Given et al., 2018). E3 was chosen as the basis of the system as it proved to be the fastest and most accurate algorithm of the three introduced above (Chung et al., 2019). In addition to EPIC, a second event source-detection algorithm called FinDer (Finite-fault Detector) has been included in the ShakeAlert platform. This finite-fault algorithm was proposed by Böse et al. (2012) to overcome the magnitude saturation challenges of point-source EEW approaches, as discussed in Regional Earthquake Early Warning Systems.

ShakeAlert combines information from the EPIC and FinDer algorithms through a decision module DM (Kohler et al., 2018). The DM receives event notifications from the EEW algorithms, which include the estimated earthquake location, magnitude and ground shaking, and creates alerts using a weighted average of the reporting algorithms (Chung et al., 2019).

The first “public” EEW in the West Coast of the United States was launched in Los Angeles in January 2019 (Hobbs and Rollins, 2019). Introduced as a smartphone application, and named ShakeAlertLA, this system provides warnings to 800,000 subscribers. Initially, the app alerted users if a magnitude 5.0+ was detected, but it was soon updated to provide warnings for Los Angeles county if earthquakes with magnitude 4.5+ were estimated. The California-wide EEW MyShake mobile application was launched in October 2019, as a collaboration between Caltech, UC Berkeley, USGS, and the Californian Office of Emergency Services (Allen et al., 2019). Both

ShakeAlertLA and MyShake are intended to deliver warnings by receiving a real-time earthquake feed from the ShakeAlert platform.

### Operational sphere

MyShake is designed to release a warning if a magnitude 4.5 earthquake, or bigger is detected by the system (Allen et al., 2019). The contents of the warning message include the earthquake’s time of arrival at a given location, as well as its location and magnitude. When it comes to individuals, warning messages include advice on how to prepare for an earthquake, such as Drop-Cover-Hold On. Aside from delivering messages, the app also works as a seismic sensor, allowing crowdsourcing of information, by storing motion and location data (for the recording mobile phone) that are immediately sent to the developers for further research and improvement of the app’s algorithms. Additionally, MyShake can be downloaded anywhere in the world, to obtain information about earthquakes that have occurred anywhere and to share individuals’ post-earthquake feedback (e.g., experiences and observations); however, EEW alerts are exclusively for Californian events. As mentioned by the developers[10], the system is still a prototype, but it is a considerable advancement towards a public EEW system in California.

### Political and governance sphere

MyShake represents a first attempt at a public EEW system for California. Obstacles to accomplishing more advanced and comprehensive EEW operability include the lack of essential related funding (e.g., Federal Government contributions). However, some researchers have shown that implementing a complete EEW system in California would be a cost-effective strategy for reducing human and economic losses due to earthquakes in the state. Strauss and Allen (2016) developed a cost-benefit analysis to understand the possible advantages of developing an EEW for the West Coast

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[10] https://eps.berkeley.edu/news/myshake-release-first-statewide-earthquake-early-warning-system

of the United States. The study pointed out that the annual cost of operating a public EEW system for the entire United States-West Coast would be repaid if it saved just three lives, warned two semiconductor plants, slowed one rapid transit train to avoid derailments, reduced 1% of non-fatal injuries, and led to a 0.25% decrease in gas-related fire damage triggered by an earthquake.

Legislative action requirements present some additional challenges to achieving a fully operational EEW service in the state of California. Johnson et al. (2016) pointed out that representatives from 24 organisations (representing 14 important sectors of the state's infrastructure and economy) declared some concerns about the levels of liability associated with decisions based on warnings given by the system, particularly those related to actions undertaken as a consequence of false warnings. Similarly, participants of the study perceived a strong relation between EEW systems and life safety, raising financial, political and equity concerns that need to be addressed in the early stages of the system's implementation. Access to the physical infrastructure of the system and the information it provides, as well as ensuring a stable governance structure and the reliability of continuous state-wide funding are key points that study participants included in the list of concerns (Johnson et al., 2016). It was argued that the inclusion of partners and stakeholders could improve the performance of broadcast notifications for EEW. Johnson et al. (2016) highlighted that representatives of the electric, telecommunications and information technology sectors should be included in the California EEW system Implementation Steering Committee, in addition to the government bodies and academic institutions already involved.

#### Social and behavioural sphere

The social perceptions of EEW in California and the West Coast of the United States strongly suggest that there is common public agreement on the need to implement the service. A survey conducted by the Probolsky Research Group in 2016 (Allen and Melgar, 2019) indicated that 88% of respondents (out of a total of 1,000) agreed that the state government should fund the warning system, and also expressed their willingness to pay small taxations to improve it[11]. Similar findings have been identified by Dunn et al. (2016), who performed a 2,595-participant study in the states of Washington, Oregon and California, suggesting again that the perceived benefits of EEW systems were enough to justify some ad-hoc small tax contributions. The survey by Johnson et al. (2016) found that availability of EEW to the wider public and local communities was viewed by relevant stakeholders as a credible way to improve earthquake educational levels, as well as to raise related awareness and preparedness of both individuals and organisations. Strauss and Allen (2016) highlighted that a West Coast EEW system could reduce injuries in earthquakes by more than half. This is because actions such as Drop-Cover-Hold On could be done in advance of strong shaking, mitigating the impact of non-structural falling hazards that accounted for 50% of the injuries in cases such as the 1989 Loma Prieta earthquake (Allen and Melgar, 2019). In addition, Porter (2016) showed that if the whole San Francisco Bay Area community were properly trained to carry out Drop-Cover-Hold On and a public EEW system was operational in the area, any advance warning that allows the implementation for Drop-Cover-Hold On would be enough for 19,000 people to avoid injuries or death. The literature identifies a further potential benefit of a publicly available West Coast EEW, which is the enhancement of psychological resilience to earthquakes. For example, the information provided by a warning may reduce anxiety and other mental disorders triggered by sudden unexpected ground shaking, as discussed by Johnston et al. (2016).

### Organisational sphere

The United States-West Coast case study lacks associated research on the organisational sphere of EEW. However, the survey by Johnson et al. (2016) provides some insights that could be used as the basis for further analysis. A first point that emerges from the survey is that some private

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[11] https://www.moore.org/article-detail?newsUrlName=poll-nearly-nine-out-of-ten-california-voters-support-earthquake-early-warning-system

companies/organisations are already investing in their own EEW systems, and it is worth investigating whether these private efforts can be redirected to improve and sustain a public service. Indeed, the 24 organisations that participated in the survey indicated that a state-wide EEW system would be a beneficial risk mitigation measure, as a few seconds of advance warning could make a positive difference to the success of measures such as Drop-Cover-Hold On. The results of the survey highlighted consensus among stakeholders that EEW could be used for increasing the safety of employees by reducing the time needed to address “life-safety issues and complete life-safety assessments by directly informing people so they can take preventative actions” (Johnson et al., 2016). Interviewees felt that EEW could enhance business continuity management by facilitating faster organisational movement and efforts, allowing a more efficient restoration of operations. It could therefore reduce organisational downtime, economic losses, and disruptions, which would benefit end users and residents that avail of the services provided by those organisations. A final point that emerged from the survey of Johnson et al. (2016) is the need to tailor risk-mitigation actions to different target sectors, given variations in life and safety concerns. For example, larger companies might have different social dynamics (i.e., behaviours of groups resulting from the interactions of individual group members) when compared to smaller ones, requiring distinct EEW trainings or scenarios that integrate some considerations of external factors such as the period of the day or night in which an earthquake occurs and its implications for working timetables or shifts. Moreover, it was evident that implementation of the EEW system requires the definition of practices and training that must be properly explained and understood, involving improved communication between the companies and first responders.

One of the partners involved in ShakeAlert is the Bay Area Rapid Transit (BART) network (trains) in San Francisco, which has implemented an automated train-braking mechanism that is triggered by the EEW system. It takes 24 s to bring a train travelling at 112 km/h to a stop; during peak commuting times, about 64 trains are in operation across the BART network-each carrying approximately 1,000 passengers-and up to 45 trains travel at 112 km/h at any one time. Even one derailment at such a speed would be devastating. Moreover, minimizing earthquake damage to trains and tracks results in faster resumptions of services, which in turn supports the post-event restart of regional businesses. The BART system responded successfully to the EEW alert before the arrival of the M 6.0 South Napa Earthquake in 2014. Despite the fact that no trains were running at the time (3:20 am), the right procedures/protocol were in place (Strauss and Allen, 2016; Tajima and Hayashida, 2018).

### 3.5.3 Japan

The original on-site EEW system of Japan (developed in 1960) is considered the oldest implementation of EEW worldwide. This system was designed to offer protection against earthquakes for high-speed trains managed by the Japanese Railway System (Nakamura and Saita, 2007). Nakamura (1988) improved the initial platform by developing the Urgent Earthquake Detection and Alarm System (UrEDAS), a front-detection algorithm to detect the arrival of P-waves and estimate earthquake source parameters. Based on 3 s of the incoming P-wave train at a single station, UrEDAS calculates the magnitude of the event, the amplitude of the recorded motion and the epicentre of the earthquake (Nakamura and Saita, 2007). Compact UrEDAS is a complementary on-site EEW approach for the protection of Japanese Railways, estimating the “expected destructiveness” of the earthquake immediately from the earthquake motion just 1 s after the station has registered the P-wave arrival. In addition to train lines, Compact UrEDAS became operational in metro systems across Japan in 1998, following the Kobe earthquake in 1995 (Allen et al., 2009b).

A nationwide EEW system has been operating in Japan since 2006, which is managed by the Japanese Meteorological Agency (JMA) (Doi, 2011). The network is formed of 1,000 seismic stations deployed around the Japanese territory, spaced 20-25 km apart (Brown et al., 2011). The system follows a step-by-step algorithm that improves the estimations of earthquake magnitude and location as time passes (i.e., as more stations record the ground motion in time).

The hypocentre of the earthquake is determined using the approach proposed by Horiuchi et al. (2005), which geometrically constrains the location using geographical information on stations that have and have not yet recorded the arrival of P-waves (Nakamura et al., 2009), similar to the RtLoc algorithm mentioned in Italy. The magnitude of the event is calculated using separate scaling relationships between magnitude and the displacement amplitudes of the recorded P- and S-waves (Kamigaichi et al., 2009); the appropriate relationship to implement at a given time step (i.e., P- or S-wave one) is determined based on the expected arrival time of the S-wave.

The magnitude and location estimates of the nationwide system are then used to predict the value of PGV on bedrock at each location of interest, according to the GMM proposed by Si and Midorikawa (2000). Site amplification factors are used to convert the calculated amplitudes to peak velocities at the surface, which are finally translated to JMA seismic intensities via an empirical model (Kamigaichi, 2004). A warning is released whenever the value of predicted JMA intensity is larger than 3 (for advanced users, such as elevators operators and factory managers) or larger than 4 (for the general public) (Hoshiba, 2014; Hoshiba et al., 2008).

Operational sphere

In Japan, warnings are disseminated to users that fall into two main categories (Hoshiba, 2014; Hoshiba et al., 2008): the first category includes online limited advanced users (organisations) that receive the warning through internet or dedicated telephone lines, which facilitates automatic actions related to their businesses (i.e., control of elevators) (Doi, 2011; Kamigaichi et al., 2009); this warning is intended for offices, schools, industry companies and critical facilities. The second group of users is the public that receive the warning and decide themselves on the optimal non-automated actions (depending on their circumstances) to be performed to mitigate their risk (Hoshiba et al., 2008). The second category of users receives the warning via media such as radio, e-mail, SMSs and the internet (Doi, 2011; Wald, 2020). The Fire and Disaster Management Agency also distributes warnings via speakers spread throughout different Japanese municipalities (Allen et al., 2009b), using a satellite communication system (J-Alert).

The contents of the warning messages differ for both categories: 1) advanced users receive the estimated magnitude and location of the epicentre, and lead time and predicted seismic intensities upon request (Doi, 2011); 2) the general public receives the earthquake’s origin time, the epicentral region name, and the names of subprefectural areas where the estimated JMA intensity is equal to or greater than four (Kamigaichi et al., 2009).

Previous work indicates that real-time warnings in Japan help to reduce seismic damage and losses for both factories/industrial facilities and critical infrastructure. For example, advanced warning facilitated by EEW enabled an electronics company located in the Miyagi Prefecture to cut the supply of chemicals in its factory 12 s before the arrival of ground shaking from the M 6.8 2007 Chuetsu-oki earthquake (Kamigaichi et al., 2009). During the same event, infants in a nursery located in the Fukushima prefecture moved into a safe zone 30 s before the earthquake hit the area. Offices, schools, shopping malls, and other factories also benefitted from the warning (Kamigaichi et al., 2009).

### Political and governance sphere

The JMA has provided training to the population of Japan since 2007, when the system was launched publicly (Tajima and Hayashida, 2018) . When an estimation is performed at a seismic station, the resulting values of earthquake source parameters and expected ground shaking are transmitted to the JMA on a real-time basis. JMA is then responsible for nationally disseminating the message, through disaster management organisations and broadcast companies (Doi, 2011). Also, many local governments (e.g., Tokyo) have installed EEW systems in public schools (Hoshiba, 2014). Kamigaichi et al. (2009) adds that implementing EEW in Japanese public facilities is a decision taken by the facility manager. JMA develops and disseminates public guidelines and manuals to understand the operability and capabilities of an EEW system put in place. These guidelines are also available to the public on the JMA's website (in Japanese only).

Social and behavioural sphere

After the 2011 Tohoku Earthquake, JMA collected 2,820 survey responses from the general public of Iwate, Miyagi, and Fukushima, aiming to understand whether these people found EEW useful in general. The results of the survey indicated that 87% of the respondents were familiar with EEW systems and found them useful (Fujinawa and Noda, 2013). Positive public reaction and agreement toward EEW implementations in Japan can be also found in Hoshiba (2014), Nakayachi et al. (2019), and Santos-Reyes, (2019). In addition, Fujinawa and Noda (2013) highlighted that the warning issued during the 2011 minor tremor provided people with a valuable chance to prepare for the strong incoming shaking. Users expressed a positive attitude toward false alarms after the Tohoku earthquake, arguing that they represented an opportunity to practice protective actions after the alarm is triggered (Allen et al., 2017). Ohara (2012) also carried out a survey in the Tokyo area to understand EEW awareness, before and after the 2011 Tohoku earthquake. The results present a remarkable increase in awareness toward EEW and the useful pre-event actions it accommodates. In addition, the results showed that after the 2011 event, people were more familiar with the technical limitations of the warning system and agreed that they prefer having a system that might provide false alarms than not having one at all (Ohara, 2012).

Warnings in Japan have clearly provided the population with enough time to implement risk-prevention strategies in past events, but Nakayachi et al. (2019) carried out a survey that revealed a possible practical issue: users tend to primarily react mentally and not physically, and therefore remain still once a warning is issued, without taking any kind of protection actions (Nakayachi et al., 2019). The reasons why most of the interviewees did not react after the alert mostly include: 1) “I expected small intensity, so I thought it was not necessary to do anything”; 2) “I thought the place I was in was safe”, and 3) “I did not know what to do”. Reason 1) seems to be related to the fact that the warning just indicated “strong shaking incoming” without any specific information about the available warning time nor the actual intensity expected at the area (Nakayachi et al., 2019) (for instance in the case of EEW delivered via speakers). It is of great concern for the JMA that individuals do not know what has to be done once the alarm is triggered (Doi, 2011). For these reasons, JMA has distributed brochures and videos among the Japanese population highlighting various scenarios that explain the best way to get prepared before the arrival of the incoming shaking (Doi, 2011). On the other hand, it has been noted that advanced users (i.e., organisations) have a clear understanding of the actions to be taken when an EEW is released (Doi, 2011).

#### Organisational sphere

Public and organisational training on various EEW risk-mitigation actions has been put in place across different companies and institutions in Japan. Drills are performed nationally to exercise actions that can be taken once the EEW is triggered (Dai, 2011; Doi, 2011; Fujinawa and Noda, 2013; Yamasaki, 2012). Different levels of organisations and individuals participate in drills across the year, including: 1) organisations (private and public ones) across the country that carry out regular mandatory drills for their employees; 2) students, who are required to participate in a drill on the first day of each academic year; and 3) the general public, who participate in a nationwide drill on “National Disaster Prevention Day”, in collaboration with local governments.

Hospitals are a key piece of critical infrastructure that could benefit from EEW in Japan, according to previous research. Horiuchi (2009) analysed potential

EEW-related actions that could be performed to protect patients, staff and delicate equipment, in a research project carried out at the National Hospital Organisation Disaster Medical Centre in Tokyo. By considering a scenario in which a patient is in the middle of a surgery when an earthquake occurs, the study provides a series of actions-both manual and automatic-that can be performed before the arrival of the tremor. Stopping elevators and opening all the doors of the premises are the main automatic actions identified for efficient evacuation of people once the EEW alarm is triggered. Interrupting medical procedures to prevent surgical errors on the patient due to shaking is the main manual EEW strategy discussed. A full list of the processes proposed can be found in Horiuchi (2009).

Finally, both UrEDAS and Compact UrEDAS provide warnings in about 90 locations along the lines of the Tokaido Shinkansen fast train, which travels with an average velocity of 360 km/h (Ashiya, 2004). If an alarm is triggered, trains are stopped if possible, or else run at low speeds to reduce potential damages.

### 3.5.4 Mexico

The Mexican EEW system was proposed by the Science and Technology National Council (CONACyT, Spanish acronym) and the Mexican National Research Council in 1986, as an urgent mitigation strategy against earthquake risk, given the M 8.1 1985 Michoacán earthquake that hit Mexico City with significant effects in terms of economic and human losses (Cuéllar et al., 2017; Espinosa-Aranda et al., 2009, 2011). In August 1991, financed by Mexican City authorities, the Seismic Alert system (SAS) for Mexico City was deployed in the south-west of the country and had 12 seismic stations in the early stages of its implementation. In 1999, the state of Oaxaca, Mexico, experienced a catastrophic M 6.7 earthquake, which triggered the construction of the Seismic Alert System of Oaxaca (SASO), consisting of a network formed of 37 front-detection seismic stations.

Encouraged by the effective alerts of the two warning systems (SAS and SASO), the governments of Mexico City and Oaxaca decided to work together to create the Seismic Alert System of Mexico (SASMEX) in 2005. Designed as a front-detection system, the Mexican EEW system provides between 60 and 120 s of warning time to Mexico City (Cuéllar et al., 2018), which is significantly longer than the lead time provided in other countries (e.g., the Campania region, in Italy, where the maximum lead times are on the order of 15-20 s). A large warning time is possible with SASMEX, given that the distance between the network and Mexico City is 320 km (on average). The government of Mexico City financially funded the extension and update of SASMEX in 2010 to improve its performance, ultimately resulting in a total number of 97 stations within the network. SASMEX seismic sensors and alarms are currently located in seven states of Mexico (Jalisco, Michoacán, Colima, Guerrero, Oaxaca, Puebla, and Mexico City), (Cuéllar et al., 2017).

The detection and classification of large earthquakes performed by SASMEX is based on the $2\ (t_s - t_p)$ algorithm (where $t_s$ refers to the arrival time of the S-wave, and $t_p$ to the arrival time of the P-wave) (Cuéllar et al., 2017). A second algorithm defined as $t_{p+3}$ was added to SASMEX in 2018, to calculate warning times for in-slab earthquakes that are located within the subducted Cocos Plate beneath central Mexico (Cuéllar et al., 2018). This algorithm does not consider S-wave arrivals, as historical events have shown that S-wave triggers result in the release of alerts that coincide with the arrival of ground shaking (no actual warning time delivered). SASMEX has proved to be an efficient and reliable system for the provision of long lead time warnings for Mexico City. In addition, it has been recognised as the first system in the world to provide public EEW (Lee and Espinosa-Aranda, 2003).

Operational sphere

SASMEX warnings are issued through speakers located across Mexico City, and also disseminated through media messages via national television and radio broadcasts (Espinosa-Aranda et al., 2009; Santos-Reyes, 2019; Suarez et al., 2009). However, the speakers do not fully cover all 16 counties of the urban area in Mexico City, leaving some regions without any alert and with fragmented information about incoming earthquakes. Other services are available, such as private repeaters or speakers, but they require private investments in order to be accessed. The thresholds to issue an alert were updated for all cities that receive warnings in April 2019. Three different threshold cases have been established for triggering the alarm: 1) the estimated magnitude is larger than five and the estimated epicentre is within 250 km away of the target city; 2) the estimated magnitude is larger than 5.5 and the estimated epicentre is within 350 km of the target city; and 3) the estimated magnitude is larger than six and the estimated epicentre is outside a radius of 350 km.

A major concern highlighted by local media in Mexico[12], is the ineffective distribution of warning devices across the states that are equipped with EEW capabilities. In 2010-11, Mexico City's government and the federal government funded the extension of the country's EEW system, paying for 88,000 extra alarming receivers. However, 60% of these devices are either stored, stolen/lost, installed excessively in some public buildings (e.g., 48 devices installed in buildings that only require 1) or simply missing in places where alarms are required, and some can even be purchased in e-shops. In addition, most of the installed speakers and receiver devices are located in the capitals of the seven states that receive alerts, such that few or no warnings are issued in other cities or towns that have been damaged in the past by ground shaking. For example, no speakers nor alarming devices were installed at the time of the September 7, 2017 earthquake in Juchitán, which was the Oaxacan town that registered the greatest number of casualties during the event.

A critical issue that commonly emerges in the literature is that the warning is limited to an alert about the incoming shaking, and does not provide any

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[12] https://www.animalpolitico.com/2017/09/gobierno-compra-alertas-sismicas-desaparecen-bodegas/

additional information about its characteristics, such as estimated arrival time and expected intensity/magnitude (Suarez et al., 2009). This incomplete information represents a major challenge, as indicated by a survey conducted after the September 2017 events in Mexico (Santos-Reyes, 2019), in which 2,400 residents of Mexico City expressed a preference for knowing the available lead time.

### Political and governance sphere

The government has consistently lacked a clear strategy for disseminating SASMEX's operational and warning procedures to end users. In addition, the system lacks efficient planning/coordination with first responders, and does not benefit from inter-agency coordination between local and federal governments (Suarez et al., 2009). Different issues have been highlighted in the analysis: first, the number of users is too low, considering the large population of Mexico City. Only a very small fraction of schools, first responders, critical service suppliers, and hospitals have access to the alerts (Suarez et al., 2009)[13]. Secondly, EEW systems are not exclusively managed by governmental bodies, presenting both advantages and shortfalls. Private organisations have developed mobile applications that provide warnings to the public located outside the range of SASMEX, improving the distribution of warnings but also creating possible sources of conflict. Reddy (2019) concludes that the most common of these applications, called "SkyAlert" might jeopardise the functionality of the official Mexican EEW system. It has been noted that predictions from SkyAlert do not always match those of SASMEX, which can cause issues in terms of the reliability of both sources (Allen et al., 2017). Santos-Reyes (2019) suggested that decision makers, such as the civil protection department of Mexico City, should strengthen their policies and efforts to raise awareness of the capabilities (and limitations) of SASMEX. This need was clearly demonstrated during the M 7.1 earthquake on September 19, 2017. For this event, the EEW alert was issued in Mexico City at the same

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[13] https://www.seismosoc.org/news/mexicos-early-warning-system-perform-recent-earthquakes/

time as strong shaking occurred, which confused residents who commonly believed that EEW would always provide 60 s of warning time between the signal and the arrival of the strong shaking (Santos-Reyes, 2019). Users of SASMEX found it less useful after this event than they had before (Santos-Reyes, 2019).

Finally, the system does not provide coverage to all areas of the country that have experienced significant damage in previous earthquakes. Neither the state of Veracruz, where the second deadliest earthquake (1920) recorded in Mexico was located (Suárez and Novelo-Casanova, 2018), nor the state of Merelos, where the M 7.1 September 19, 2017 earthquake occurred, receive alerts from SASMEX.  Other states of Mexico that have experienced the effects of earthquakes and do not receive EEW alerts include Estado de México and Tlaxcala[14] . Finally, it has been shown that a denser seismic network in Mexico City could have resulted in a warning time of more than 20 s for the M 7.1 September 19, 2017 earthquake, instead of the 0-6 s lead time that actually occurred (Cuéllar et al., 2018; Santos-Reyes, 2019; Tajima and Hayashida, 2018).

Social and behavioural sphere

The lack of policies on delivering EEW-related training to the public is reflected in the socio-behavioural sphere. There is general agreement among the public that EEW is useful, but the majority of end users lack adequate training or tend to ignore the appropriate protection procedures to follow before, during and after an earthquake (Santos-Reyes, 2019; Suarez et al., 2009). Different analyses indicate that decision makers in Mexico need to improve communication and education practices among the residents of Mexico City, so that they react more efficiently to warnings and have a better understanding of the capabilities and limitations of SASMEX (Espinosa-Aranda et al., 2011; Santos-Reyes, 2019). Finally, it is important to note that residents from Mexico City view false and short-notice alarms as useful opportunities to conduct

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[14] https://www.milenio.com/estados/cuantos-estados-cuentan-con-alertas-sismicas

"additional exercises" (i.e., drills) on evacuation procedures (Allen et al., 2017, 2018; Reddy, 2019).

Organisational sphere

All strategic buildings like hospitals, security buildings and offices, are legally required to contain devices for receiving EEW alerts in Mexico City (Suárez et al., 2018). Since 2015, more than 12,000 warning EEW speakers and devices have been installed across the city to broadcast alerts to different organisations and the general public (Santos-Reyes, 2019). However, the clear lack of training and information about response actions discussed previously is a major issue at the organisation level, as it reduces the potential benefits of EEW for business continuity management (Suarez et al., 2009)[13]. A lack of communication between organisations and local and federal governments means that there is no formal strategy for identifying and prioritising critical infrastructure, lifelines, and institutions to receive EEW alerts (Suarez et al., 2009).

On the other hand, drills are widely organised to practise the various risk-mitigation actions facilitated by the long warning times of SASMEX. For example, schools carry out these training procedures regularly (Suárez et al., 2018) and some critical facilities in Mexico City undertake EEW evacuation drills as part of their organisational procedures. A nationwide drill has been carried out once a year since 1986[15], when the National System of Civil Protection was launched in Mexico following the 1985 earthquake[16]. Two more annual national drills ("Macrosimulacros") were initiated in 2020.

Finally, EEW has been integrated into the organisational resilience of the Mexico City Metro (subway) (Cuéllar et al., 2014). Using radio receivers, the manager of the EEW system notifies train operators when it is necessary to stop trains and open the doors at the nearest station, so passengers can look

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[15] https://verne.elpais.com/verne/2017/09/27/mexico/1506531283_511876.html

[16] https://mvsnoticias.com/noticias/estados/realizara-cnpc-macrosimulacro-de-sismo-en-septiembre/ (in Spanish).

for earthquake protection. However, the passengers do not receive the alarm while inside the carriage when the train is moving (Espinosa-Aranda et al., 2011).

## 3.6 Discussion

From the technical perspective, engineering-related research and development of EEW applications have not yet been emphasized, although very rapid improvements of EEW are being observed in the seismology community, as also noted in Earthquake Early Warning Systems: Physical Grounds, Technical Concepts, Methods, and Perspectives. An advanced, real-time PBEE framework is recommended for the design of structure-specific applications of EEW as an improved means of reducing casualties, economic and functionality losses due to earthquakes. Such a PBEE framework would require 1) accurately characterising EEW-related uncertainty through an evolutionary and probabilistic approach for real-time seismic source and ground shaking modelling; 2) developing innovative computational building models for seismic alert and rapid damage assessment; and 3) pioneering technological and methodological solutions for interfacing real-time earthquake monitoring and engineering applications. This framework could additionally be unified with multi-criteria decision-making tools, to create an advanced engineering-oriented decision support system for EEW that explicitly accounts for end-user preferences toward expected consequences associated with each potential action. The final goal of this type of system would be to enable end users to determine optimal real-time risk mitigating actions within the context of appropriately propagated and dynamically quantified uncertainties. This would ultimately increase the effectiveness of EEW within the continuum of technical risk-mitigation strategies that currently exist for earthquakes (Wald, 2020).

The four considered case studies highlight various common lessons learned from existing EEW systems. An interesting finding from countries with public EEW (i.e., Japan and Mexico) is that there is a clear tendency by residents to accept and tolerate false alarms (Allen et al., 2017, 2018; Reddy, 2019; Wald, 2020), which provide an opportunity to perform some additional evacuation exercises to those already implemented by institutions and governments. This evidence is in line with additional existing literature (Goltz, 2002), which indicates that false alarms can be perceived as unscheduled, inexpensive, evacuation exercises or drills. Finally, it has also been found in both Mexico and Japan that users prefer to receive false alarms from an implemented EEW system rather than not having any public EEW installed. However, no case study addresses possible negative mental health consequences that might be triggered in individuals given a false alarm. This is a significant gap in the state-of-the-art, as negative mental health effects could be particularly detrimental for people of vulnerable categories, such as those affected by Post-Traumatic Stress Disorder, which is the most common mental condition among earthquake survivors (Farooqui et al., 2017). As indicated by McBride et al. (2020), releasing too many false alerts can significantly reduce the public's trust in a public EEW alert system, potentially endangering people if they consequently fail to take fast protective actions when necessary. To enhance trust in EEW, all of its limitations should be clearly communicated to end users and the public, including the potential for false alerts as well as very short warning times in specific areas (Wald, 2020).

A further element to consider in the discussion is the opinion of the public regarding EEW warnings across the case-studies. Public opinion of EEW warnings is a product of cultural or social features and is therefore region-specific. In Japan, most of the literature shows that residents of the country agree with the implementation of EEW and find it useful. However, Nakayachi et al. (2019) highlight that this is not always the case. In some regions of the country, the public does not believe that EEW alerts are effective, given their lack of detailed information about the strength of the incoming ground shaking and the expected arrival time. Related to the Mexican case-study, there is a common desire expressed by the public to receive more detailed information on the incoming event, so that the optimal risk-mitigation action can be undertaken (Santos-Reyes, 2019). This desire is shared worldwide, including by over 200 participants (organisations) of a survey that assessed the factors influencing organisational acceptance and use of EEW systems in California (Goltz, 2002). Tajima and Hayashida (2018) conclude that some types of information that can be used to determine the most appropriate actions to take, such as the arrival time, should be also be considered. In particular, the survey respondents in the study by Goltz (2002) indicated that mitigation actions such as ‘moving away from falling objects’ or “shutting off gas lines” are the most appropriate measures in a short warning time (10 s), while “evacuating to an outside area” or “shutting down hazardous materials” are more effective options when a longer warning time is available (50 s). However, positive opinion on the use of detailed EEW alerts is not shared by other authors. For instance, Allen and Melgar (2019), Shrivastava (2003), and WMO (2017) argue that the processing of many details can delay responses, while simple warnings facilitate direct actions such as Drop-Cover-Hold On. Lindell et al. (2007) also indicates that warnings should be simple, clear and non-ambiguous, using appropriate language in a diverse environment. Finally, studies in the United States (Dunn et al., 2016) and Iran (Asgary et al., 2007) have identified public willingness to pay small taxations to contribute to the funding of EEW systems.

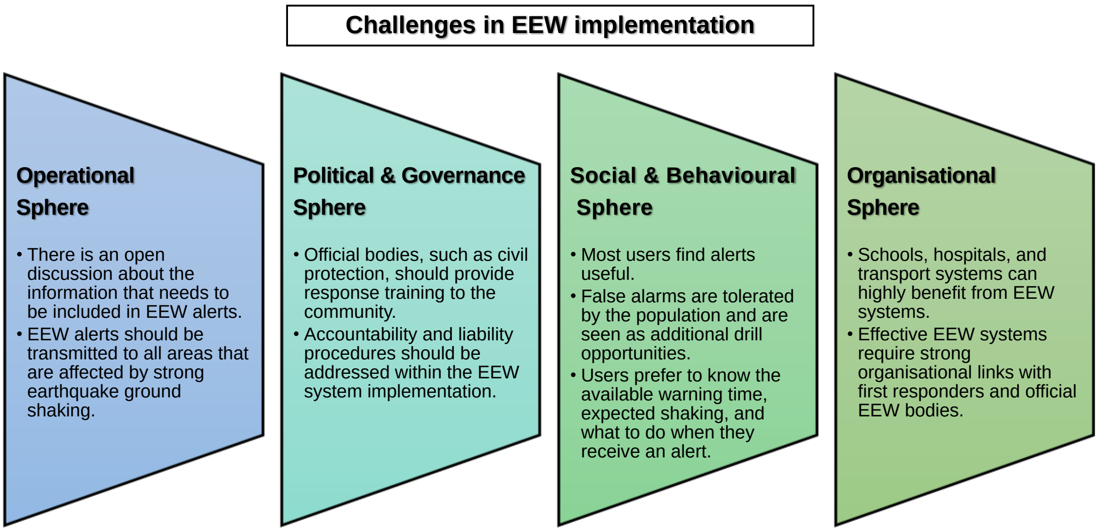
Official bodies, such as civil protection departments, are consistently regarded as crucial actors for the delivery of EEW training and education to the population (Gasparini et al., 2011), across all case studies examined. Concerns about the lack of effective political and organisational leadership related to EEW has been expressed in Mexico. For example, Santos-Reyes (2019) suggested that decision makers, such as the civil protection department of Mexico City, should increase their efforts to coordinate good practices of response to warnings, for instance through drills. This gap between EEW and monitoring services (civil protection and geological surveys) in Mexico has also been highlighted by Alexander (2015). Strong organisational links with representatives of official bodies and first responders are also required to make EEW a successful tool for enhancing business continuity in critical infrastructure such as energy, utilities, food supply, communications, and banking (Gasparini et al., 2011). As indicated by Tajima and Hayashida

(2018), EEW systems are only effective if the resilience, strength, and operations of the system are ensured before ground shaking occurs.

Public transport systems, hospitals and schools are the most typical institutional beneficiaries of EEW (Gasparini et al., 2011). In all case studies examined, the transportation sector (i.e., the Circumvesuviana railway system in Naples, the BART system in San Francisco Bay Area, the Shinkansen train system in Japan and Mexico City's Metro) has particularly clear potential to significantly benefit from EEW implementation. When a warning is released, these utilities can rapidly activate procedures to slow the traffic and to stop carriages to prevent likely damage and allow evacuation of occupants, if feasible. Similarly, it has been shown that schools can benefit from EEW because the consequences of false alarms will not be costly, but the alarms may have significant benefits for safety and support long term public education (Goltz, 2002). When it comes to hospitals, Horiuchi (2009) has listed a comprehensive series of protection/safety actions that can be carried out to safeguard the public, staff, equipment and materials, and the facilities themselves (e.g., operating rooms). These actions might reduce injuries and deaths of hospitals users and can allow a quick recovery and maintenance of facilities after an earthquake.

Figure 11 synthesises the evidence derived from this discussion and summarises the general findings for each sphere, considering all the case studies. The operational sphere, the political and governance sphere, the social and behavioural sphere, and the organisational sphere provide complementary considerations for the design and implementation of the technical components. This design and implementation process also requires a deep understanding of the local context as well as the prevailing application of legislative procedures, organisational standards and compliance assessments.

The next section will introduce some open questions for future research and practice.



**Challenges in EEW implementation**

**Operational Sphere**

- There is an open discussion about the information that needs to be included in EEW alerts.
- EEW alerts should be transmitted to all areas that are affected by strong earthquake ground shaking.

**Political & Governance Sphere**

- Official bodies, such as civil protection, should provide response training to the community.
- Accountability and liability procedures should be addressed within the EEW system implementation.

**Social & Behavioural Sphere**

- Most users find alerts useful.
- False alarms are tolerated by the population and are seen as additional drill opportunities.
- Users prefer to know the available warning time, expected shaking, and what to do when they receive an alert.

**Organisational Sphere**

- Schools, hospitals, and transport systems can highly benefit from EEW systems.
- Effective EEW systems require strong organisational links with first responders and official EEW bodies.

*Figure 11. Challenges in implementing EEW systems: common findings from the case studies, across all examined spheres.*

## 3.7 Conclusions

This chapter developed a state-of-the-art review of the technical and socio-organisational components of EEW systems. This included a detailed discussion of specific evidence from case studies of Italy, California, Japan and Mexico, where EEW systems have reached varying levels of maturity. The overall aim was to highlight improvements that are necessary to increase the effectiveness of the technical aspects of EEW in terms of their implications on the operational, political, social, behavioural, and organisational drivers.

From the technical perspective, EEW systems have benefitted from extensive seismology-related research and development and are now capable of rapidly yielding source characteristics/expected shaking estimations to a high degree of accuracy. However, engineering applications of EEW, which have the potential to significantly improve risk predictions (and therefore decision-making on the triggering of EEW alerts) for incoming events, rarely feature in the literature and are not used in real-life EEW implementations. Some studies have proposed to integrate the PBEE mathematical framework with EEW to quantitatively link seismological parameter estimations with structural performance consequences in real-time, while explicitly tracking all related uncertainties. Further work has suggested combining PBEE with multi-criteria decision-making (MCDM) techniques, to explicitly account for end-user preferences when determining real-time optimal risk-mitigation actions. A unified PBEE-MCDM approach would transform EEW into a powerful end-user-driven risk-management strategy for supporting seismic resilience.

In addition to significant technical improvements, there has been an increased awareness since the early 2000s around topics such as “people-centred’ EEW systems. However, many multi- and cross-disciplinary aspects of EEW remain relatively unexplored, which could compromise EEW’s overall goal of increasing resilience and capacity.

First, the review has highlighted some open issues in the operational and socio-behavioural spheres. Most users find alerts useful and tolerate false alarms, viewing them as additional drill opportunities. However, there is an open discussion about the information that needs to be included in EEW alerts. The literature suggests that a ‘simple warning’ (e.g., no provision of the available warning time nor the characteristics of the incoming earthquake-induced ground shaking) is typically not preferred by users. Instead, they desire to know the available warning time, expected shaking, and what to do when they receive an alert. Similarly, organisations need information to facilitate the activation of prudent/cautious mitigation actions together with alert signals. It is worth noting that some literature argues that simple warning message may be enough and optimal as the processing of many details can delay responses, while simple warnings facilitate direct actions such as Drop-Cover-Hold On. This leads to open questions such as: *What type of information is necessary to be communicated in EEW alert messages, to maximise their effectiveness? How should alert thresholds be determined, considering false alarm tolerance levels? How can a company perform shutdown operations if the time before the arrival of the shaking is unknown? What are the circumstances in which individuals evacuate, in a highly uncertain scenario?*

Secondly, this review indicates that the effectiveness of EEW can be reduced by negative reactions within the political and governance sphere, and the organisational sphere. There is often little or no coordination between official bodies that provide warnings, and those organisations that may benefit from reliable EEW. For example, even where the technical components of EEW are perceived as useful, a lack of integration in operational functions and procedures can hamper their positive impact. The technical component may also be negatively influenced by the local context in terms of legislation, standardisation, compliance, and management culture. Information and action on the political and governance sphere require special consideration when implementing EEW systems (Gasparini et al., 2011; Goltz, 2002). Complementary assessments should investigate questions such as *Who is accountable for activating emergency procedures, following an alert, within an organisation? Who is accountable for issuing alerts*? *What are the legal liabilities of disseminating false alerts*?

All the examined case studies indicated that EEW is perceived as beneficial for critical infrastructure resilience. This review showed that hospitals, public transportation, and schools have particular potential to undertake risk mitigation actions when an EEW alert is received, assuming that the warning time is enough. However, Wald (2020) argues that there are only a limited number of EEW applications to critical infrastructure that have been well documented in the literature, many of which are hypothetical. In conclusion, further research is needed to understand if *critical infrastructure should really be a priority target for EEW?*

While this work is not exhaustive, it has leveraged a few pertinent case studies to provide important insight on the technical and socio-organisational components of EEW, and how their integration may be improved for more effective promotion of seismic resilience.

# Chapter 4. A loss-based control algorithm for magnetorheological dampers combined with EEW

## 4.1 Introduction and Motivation

In practice, two fundamental problems in EEW restrict its applications: short warning time, particularly close to the epicentre, and considerable uncertainty on the predicted ground motion (Iervolino et al., 2009). EEW information always involves some uncertainty, and some EEW applications may lead to a substantial economic loss if a false alarm occurs (Iervolino et al., 2006). Therefore, deciding whether to take mitigation actions should be based on an advanced loss analysis. Moreover, as the available warning time is short, human intervention would likely take too long for any actions from being activated promptly. Therefore, automated decision and mitigation actions are favoured.

Some studies (e.g., Iervolino et al., 2010) have discussed the semi-active control of structures as a possible advanced engineering application of EEW, especially in areas where the available warning time is very short (near the so-called *blind-zone*). In this scenario, a building can change its dynamic properties within a few seconds (or milliseconds) to better withstand the approaching ground shaking. The combined use of EEW and structural control may reduce the structural vulnerability (and resulting losses) of specific systems, for example, critical infrastructure such as hospitals, fire stations, networks, etc., which have to be operational for emergency management purposes during or right after the event. As earthquakes often affect power supplies, semi-active devices are a sensible option for seismic mitigation as they can easily operate on back-up power. However, one of the key issues in using EEW with semi-active control is to properly account for the uncertainty in the EEW-based estimation of the event features: the effectiveness of such applications greatly depends on the quality of the pre-arrival ground motion information provided by the EEW system.

In this chapter, MR dampers are proposed to change the mechanical properties of a hosting structure according to information on an incoming earthquake provided by an EEW system. In particular, this chapter proposes a loss-based probabilistic framework to derive an optimum structural control strategy minimizing potential losses from an incoming earthquake.

The present chapter is organized as follows. First, the basic concepts of (1) Real-Time Probability Seismic Hazard Analysis (RTPSHA) for EEW applications; and (2) structural control, with special focus on MR dampers, are provided. Next, the proposed loss-based control algorithm for MR dampers combined with EEW is described, followed by the description of the illustrative example used in the chapter. The final sections discuss the results and offer some conclusions.

## 4.2 Background

### 4.2.1 Real-Time Probabilistic Seismic Hazard Analysis (RTPSHA)

A regional EEW system is based on a dense sensor network covering a geographical area of high seismicity. When an earthquake occurs, the relevant source parameters (event location and magnitude) are estimated from the early portion of recorded signals (initial P- waves) at sensors closest to the epicentre. The estimated source parameters can then be used to predict, with quantified confidence, a ground motion IM at a distant site where a target structure of interest is located. Specifically, recent efforts of real-time seismology on rapid assessment of earthquake magnitude and location (Zollo et al., 2014b) enable to provide an estimate of the event's features from a few seconds to a few tens of seconds before the ground motion arrives at a target site. When an event occurs, probabilistic distributions of magnitude (M) and source-to-site distance (R) are available, conditional on some parameters measured in the early portion of the P- (and sometimes S-) wave trains at a number of near-source stations. These parameters are generally associated with the low-frequency content of the data, which is sensitive to the seismic moment, and can be related to the maximum amplitude, the dominant frequency or the energy released by the event (Zollo et al. (2014b), for a comprehensive review of these parameters and related EEW models). The prediction of different IMs, conditional on those parameters, may be performed by analogy to the well-known probabilistic seismic hazard analysis (PSHA) but in real-time (Convertito et al., 2008; Iervolino et al., 2006) as formulated in Eq. (1).

$$f_{IM,n}\left(IM \mid \underline{\tau},\underline{s}\right)=\int_{m}\int_{r} f_{IM}\left(IM \mid m,r\right)\ f_{M}\left(m \mid \underline{\tau}\right)\ f_{R}\left(r \mid \underline{s}\right)\ dm\ dr \qquad (1)$$

where $f_R\left(r \mid \underline{s}\right)$ is the PDF of R conditional on the sequence according to which *n* stations triggered (at a given time *t*), $\underline{s}=\left\{s_1,s_2,...,s_n\right\}$, $f_M\left(m \mid \underline{\tau}\right)$ is the PDF of M conditional on the measures from the *n* stations triggered (at *t*), $\underline{\tau}=\left\{\tau_1,\tau_2,...,\tau_n\right\}$, and can be expressed analytically using Bayes' theorem (Iervolino et al., 2006); $f_{IM}\left(IM \mid m,r\right)$ is the PDF of the considered IM conditional on M and R, e.g., from a ground motion prediction equation (GMPE). The vector $\underline{\tau}=\left\{\tau_1,\tau_2,...,\tau_n\right\}$ may include any possible parameter estimated from the early portion of recorded signal. It was shown in (Iervolino et al., 2007a) that $f_M\left(m \mid \underline{\tau}\right)$ depends on the measures only via the summation of the logs, $\hat{\tau}=\sum_{i=1}^{n} ln\left(\tau_i\right)$ and *n*. The modal value of R alone may adequately represent its PDF due to the negligible uncertainty involved in the earthquake location rapid estimation methods. Therefore, because the GMPE is a static piece of information (not depending on the real-time measures), the RTPSHA integral may be computed offline for all possible values of the $\hat{\tau}$ and R pair, and the result has only to be retrieved in real-time without the need for computing it. This is an attractive feature of the proposed approach (Iervolino, 2011).

Eq. (1) results time-dependent hazard curves which may be used as a support tool for automated decision-making to reduce the expected loss of specific structures/infrastructures in the framework of PBEE, even in those cases where limited lead-time renders evacuation unfeasible. However, real-time IMs predictions are performed in very uncertain conditions linked to both the real-time estimation of source parameters and the traditional uncertainties involved in PSHA (e.g., (Baker, 2008).

## 4.3 Structural Control

Structural control is an additional tool that can be used to meet desired performance objectives within the framework of PBEE. Over the past decades, several control devices and algorithms have been proposed to mitigate the dynamic response of a structure during extreme events such as earthquakes and strong winds (Soong and Spencer Jr, 2002).

There are mainly three classes of control devices. Passive devices, which require no external power, are reliable and never destabilize the structure. Such devices reduce the seismic demand on the structure either by increasing the energy dissipation potential (i.e., increasing structural damping) and/or by changing its fundamental oscillation period moving it away from the most energetic frequency content of ground motion (e.g., seismic base isolation). However, they have low adaptability if the actual external loading conditions or usage patterns are different from those they were designed for. This makes integrating EEW with passive control systems difficult.

On the other hand, active control devices are adaptive to varying usage patterns and loading conditions. Such devices supply control forces based on feedback from sensors (located near to/on the structure) that measure the excitation and/or the actual response. The recorded measurements from the response and/or excitation are processed by a controller which, based on an algorithm, operates actuators producing the forces. However, generating control forces by electromechanical or hydraulic actuators requires power sources of the order of tens of kilowatts for small structures and may reach several megawatts for large structures. This, together with their stability problems and overall reliability, are still major concerns to engineers.

Moreover, active control strategies are usually based on information about the full waveform or structural response which cannot be predicted by EEW.

Semi-active devices, combining the versatility and adaptability of the active devices and the reliability of the passive devices, have attracted considerable attention for the seismic protection of structures in recent years (Dyke et al., 1996; Pohoryles and Duffour, 2015; Soong and Spencer Jr, 2002; Spencer and Nagarajaiah, 2003). These devices develop control forces based on the feedback from sensors that measure the excitation and/or the response of the structure and do not input energy to the structure (so, they usually do not induce an adverse effect on the stability of the structure). The stiffness and/or damping properties of a structure can be adjusted according to the instantaneous (measured) response of the hosting structure (feed-back) and/or to the instantaneous (measured) properties of the earthquake input (feed-forward). In both cases, a control algorithm describes the relationship between the observed quantities (e.g., displacements/velocities/accelerations of the structure, accelerations of the ground) and the corresponding optimal values of stiffness and damping (which can be changed employing electrical signals) of the adjustable devices. The energy required for the modification of the basic parameters of a semi-active device is small compared to that needed to operate conventional actuators (generally approximately tens of watts, so simple batteries can supply it - e.g., to open/close a valve).

Several strategies have been proposed to control the behaviour of semi-active devices (e.g., Spencer and Nagarajaiah, 2003). Each of the proposed control strategies has its own merits and limitations depending on the specific application and desired performance. Comparative studies are needed to evaluate the performance of each control method. As an example, Barroso and Winterstein (2002) described a methodology, referred to as *probabilistic seismic control analysis*, for the development of probabilistic seismic demand curves for structures with supplemental control devices. The proposed methodology is applied to case-study structures (3- and 9-storey) equipped with three different control systems, namely (i) base isolation (passive), (ii) linear viscous brace dampers (passive); and (iii) active tendon braces. Results from this chapter indicated that no single control strategy is the most effective for all the hazard levels/return periods.

### 4.3.1 MR dampers

One of the most promising semi-active devices is the MR damper. These are semi-active damping devices first investigated in the context of civil engineering by Dyke et al. (1996). A magnetorheological fluid is an oily liquid containing iron micro-filings. When no magnetic field is present, the iron particles are randomly dispersed in the fluid and affects little its underlying viscosity. When the MR fluid is subjected to a magnetic field, the iron micro-particles align and form linear chains which increase the fluid viscosity by several orders of magnitude. Like conventional viscous dampers, MR dampers consist of a fluid-filled cylindrical chamber along which a tightly fitting piston moves. In this case, however, the chamber is filled with MR fluid and is wrapped within an electric coil. Supplying the coil with a current induces a magnetic field in the fluid and changes its viscosity. By varying the current in the coil (through an input voltage), the magnitude of the force developed in the damper can be controlled. MR dampers adapt with very fast response times (i.e., < 1s including trigger and set up time (Occhiuzzi et al., 2003) over a broad temperature range and have low power requirements. They are relatively inexpensive to manufacture and maintain. During the last few decades researchers have investigated both numerically and experimentally the behaviour of MR dampers and semi-active control algorithms associated with these types of dampers for earthquake hazard mitigation (Wang and Liao, 2011). Figure 12 shows the force-displacement and force-velocity loops for a small-scale prototype MR damper subjected to harmonic cycles (constant amplitude of 1.5 cm and frequency of 2.5 Hz) for varying input voltage levels. It is clear from these graphs that MR damper behaviour is highly nonlinear and voltage-dependent.

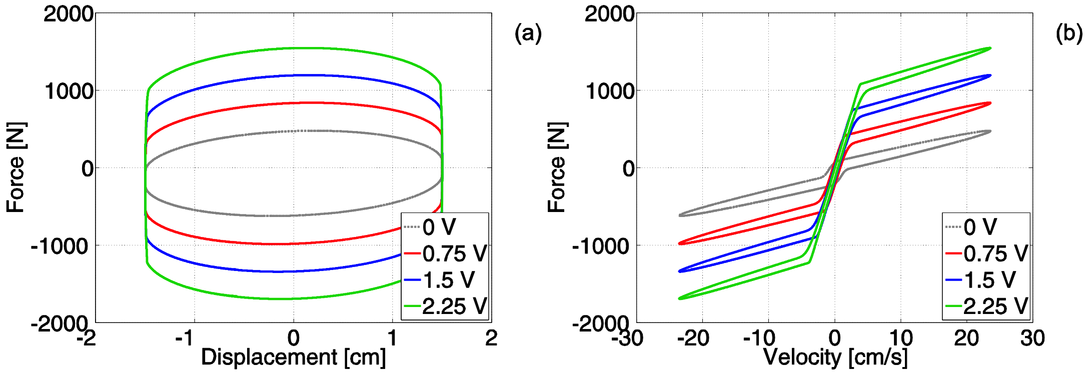


*Figure 12. Force-displacement (a) and force-velocity (b) loops for a small-scale prototype MR damper for imposed harmonic cycles at different current levels.*

For structural control MR dampers can be used either in passive or semi-active mode. In passive mode, illustrated in the block diagram shown in Figure 13, a constant current is supplied to the MR damper. No feedback data are required, and the damper force is generated passively by the movement of the damper. In the remainder of the chapter, passive-on and passive-off controls refer to the cases when the maximum and no current, respectively, are supplied to the damper.

The semi-active controlled system shown in Figure 13 uses feedback data, requiring the use of sensors (e.g., accelerometers, load cells, displacement transducers), and a controller to determine the damper control force.

A basic semi-active control algorithm is based on the simple on/off command current rule. The state of the structure is assessed, and the controller determines if increasing the damper force is beneficial to reduce the response of the structure. If so, the semi-active controller inputs the maximum current (i.e., on-mode) to the damper to maximize the benefit. Otherwise, it just inputs the minimum current (i.e., off-mode).

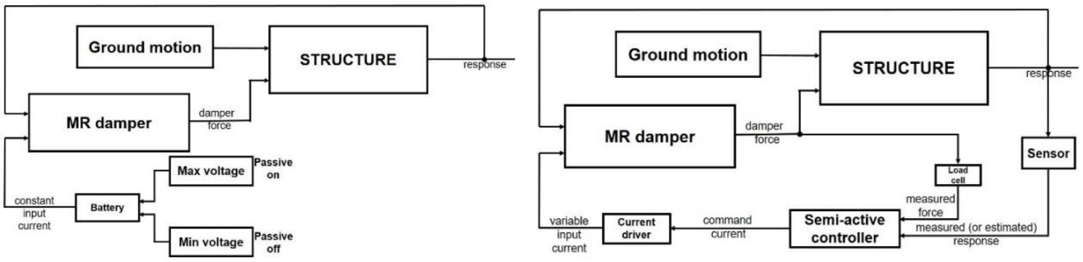


*Figure 13. Block diagram for a passive controlled system with MR damper (left); Block diagram for a semi-active controlled system with MR damper (right; adapted from* (Chae et al., 2013)*.*

More sophisticated control algorithms can be used to control MR dampers (e.g., decentralized bang-bang Control, Maximum Energy Dissipation, Clipped-Optimal Control, Jansen and Dyke, 2000). Following Maddaloni et al. (2013), this study uses MR Dampers in a “passive smart” mode: the mechanical properties of the device are set just before the arrival of a seismic event at a site, according to the IM estimate of the incoming earthquake provided by the geographically relevant EEW system (Figure 14). This adjustment is supposed to only happen once, keeping the device control parameter unaltered for the whole duration of the seismic event. Herein, this control strategy is referred as ‘SA+EEW’. Later in the chapter it will be compared to the passive strategy (coil fed with the maximum voltage) and a semi-active strategy proposed by (Pohoryles and Duffour, 2015) called the Improved-Clipped Algorithm ('SA ICA'). 'SA ICA' represents an improvement of the clipped-optimal control algorithms for MR dampers introduced by Dyke et al. (1996) and Yoshida and Dyke (2004).

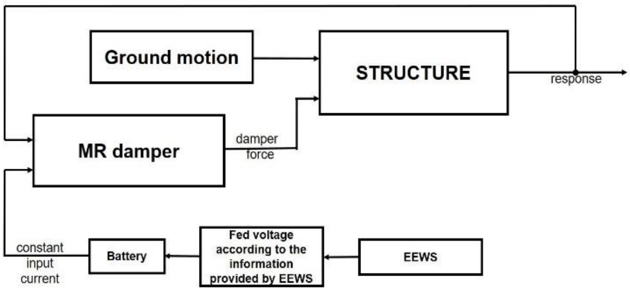


*Figure 14. Block diagram for a smart passive controlled system with MR damper combined with EEW.*

It is worth noting that the study presented in Maddaloni et al. (2013) has several limitations which are addressed here: PGA is used as the selected IM in their study, stating that ‘the research to reliably predict the complete elastic spectrum is still in progress’, not considering the study of Convertito et al. (2008); only 16 ground motion records were used in the calibration of the control algorithm based on EEW, with low statistical significance of the presented results; the uncertainty analysis performed to investigate the sensitivity of the results to uncertainty in the EEW real-time estimates is based on simplified assumptions/models; the control algorithm is based on the reduction of peak response quantities of a benchmark highway bridge rather than in terms of expected loss. This last point is particularly important: the designed algorithm should provide the optimal value of voltage that would provide the optimal structural response considering all the EDPs of interest. Given that different EDPs represent different physical quantities (with different units) and show different trends as function of the input voltage in the MR damper, a loss-based algorithm is the only option able to incorporate the representative contribution of all the EDPs taken into consideration.

## 4.4 Loss-Based Control Algorithm for MR dampers

The loss estimation approach used in this chapter is primarily based on the simplified storey-based building-specific loss estimation method proposed by Ramirez and Miranda (2009). To develop a building-specific relationship linking ground motion with an intensity level of IM to the expected economic monetary loss (L), Eq. (2) can be used:

$$E\left[L\,|\,IM\right]=E\left[L\,|\,NC,IM\right]P\left(NC\,|\,IM\right)+E\left[L\,|\,C\right]P\left(C\,|\,IM\right) \tag{2}$$

where $E\left[L\,|\,NC,IM\right]$ is the expected loss in the building given that collapse has not occurred at the given IM level; $E\left[L\,|\,C\right]$ is the expected loss given that the building has collapsed (i.e., cost of removal of debris from the site plus replacement value); $P\left(NC\,|\,IM\right)$ is the probability that the building does not collapse at the given IM level; and $P\left(C\,|\,IM\right)$ is the probability the building does collapse at the given IM level (which is complementary to $P\left(NC\,|\,IM\right)$, i.e., $P\left(NC\,|\,IM\right)=1-P\left(C\,|\,IM\right)$). $P\left(C\,|\,IM\right)$ can be quantified by using nonlinear structural simulation (e.g., Haselton and Deierlein (2008); in this chapter, $P\left(C\,|\,IM\right)$ is determined using the results of nonlinear dynamic analysis by establishing a collapse criteria based on maximum Interstorey Drift Ratio (MIDR), i.e., collapse occurs if MIDR is larger than 10%. At this level of deformation, it is assumed that the building will not be able to recover a stable position and side-sway collapse will be initiated.

$E\left[L \mid NC,IM\right]$ in Eq. (2) can be computed using a storey-based approach by grouping individual component losses per storey and pre-computing estimated damage using assumed cost distribution of the total storey value, Eqs. (3) to (5):

$$E\left[L \mid NC,IM\right] = \sum_{i=1}^{\#story} \sum_{k=1}^{3} E\left[L_{i,k} \mid NC,IM\right] \tag{3}$$

$$E\left[L_{i,k} \mid NC,IM\right] = \int_{edp} E\left[L_{i,k} \mid NC,EDP_k\right] \left| dP\left(EDP_k > edp_k \mid NC,IM\right)\right| \tag{4}$$

$$E\left[L_{i,k} \mid NC,EDP_k\right] = \sum_{j=1}^{\#DS} E\left[L_{i,k} \mid DS = ds_j\right] P\left(DS = ds_j \mid NC,EDP_k\right) \tag{5}$$

In Eq. (4), $E\left[L_{i,k} \mid NC,IM\right]$ is the expected loss (eventually normalized by the original cost of the component or its replacement value) at the *i*-th storey for the *k*-th component category given that collapse has not occurred at the given IM level; $E\left[L_{i,k} \mid NC,EDP_k\right]$ is the expected loss (normalized by the original cost of the component) at the *i*-th storey for the *k*-th component category conditional on non-collapse and the EDP associated with the *k*-th component category $\left(EDP_k\right)$; and $P\left(EDP_k > edp_k \mid NC,IM\right)$ is the complementary cumulative distribution function (CCDF) of $EDP_k$ conditional on non-collapse and the given IM level and can be computed by using nonlinear structural simulation (e.g., Jalayer and Cornell, 2009). In Eq. (5), $E\left[L_{i,k} \mid DS = ds_j\right]$ is the expected loss (eventually normalized by the original cost of the component) at the *i*-th storey for the *k*-th component category given that collapse has not occurred at the given damage state $\left(ds_j\right)$; $P\left(DS = ds_j \mid NC,EDP_k\right)$ is the probability of being at (or exceeding) a damage state $ds_j$ conditional on the EDP level associated with the *k*-th component category (i.e., component-specific fragility functions, see Aslani and Miranda (2005).

The seismic demand (in terms of an EDP) due to seismic excitation can be estimated by performing a Probabilistic Seismic Demand Analysis (PSDA) on a computational model of the building. One possible approach in PSDA (used in this chapter) is to apply a series of earthquake ground motion time histories to the building model and to estimate the peak responses at different levels along the building height. For the purpose of loss estimation described above, the structural response has to be evaluated at all stories in terms of the EDPs that have the closest correlation with the damage in the components. Three broad categories of components are considered here: (1) drift-sensitive structural components; (2) drift-sensitive non-structural components; and (3) acceleration-sensitive components. Hence, an inventory of components and their location within the structure is required.

The main output from PSDA is the probability distribution of the structural response, namely IDR and PFA, at different locations and at different levels of intensity. For each category of components, fragility functions can be used to estimate the probability that a particular building component will reach or exceed different damage states as a function of the EDPs. The repair or replacement cost of a component can finally be estimated by itemizing the tasks that need to be accomplished after the occurrence of each of the damage states.

The main objective of the approach proposed here is to set the input voltage *u* to the MR damper, within the range 0-$u_{max}$, according to a given control algorithm *u*(IM) so as to obtain the minimum expected loss during the seismic excitation. The given IM value to input into the control algorithm can be the expected value of the real-time distribution of the considered IM (derived through the RTPSHA).

To calibrate the $u$(IM) algorithm, a set of nonlinear time-history analyses can be performed using a set of (unscaled) ground motion records; for each ground motion record, the MR damper is fed with a range of voltage values (0-$u_{max}$ with a given step $\Delta u$), always keeping the input voltage constant for the whole duration of the event. For each ground motion, the value of the different EDPs is computed (for each voltage) and the optimal value of voltage $u_{opt}$ – the one leading to the minimum expected loss – is recorded. Eq. (5) is used to estimate each component expected loss (at each storey) as a function of the EDP (corresponding to a given ground motion record - characterized by a given IM and voltage value) and to select $u_{opt}$ for the given IM. Robust regression can be finally used to fit an analytical control model to the obtained (IM, $u_{opt}$) values.

Eqs. (3) and (4) can be used to estimate the component expected loss (at each storey) and the total expected loss as a function of the level of intensity IM. This result can be used to compare the expected loss for different control strategies for different hazard levels and test the effectiveness of the proposed integration between smart passive MR damper and EEW.

## 4.5 Case-study

A numerical example is presented in this section to illustrate how to implement the loss-based control algorithm for MR dampers combined with EEW, as discussed above. The numerical example consists of a scaled three-storey building structures modelled in Simulink® as a simple three-degree-of-freedom shear frame. It is fitted with an MR damper connecting the ground and first floor (Figure 15). The location(s) for the control devices in the structure could be changed to optimize the structural performance but the particular topology shown in Figure 15 is adopted because it has been widely used by other researchers testing different control strategies employing MR dampers in the past (e.g., Pohoryles and Duffour, 2015). The structure has a fundamental period $T$ equal to 0.2s and its fundamental structural properties, mass (M), damping (C), and stiffness (K) are:

$$M = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} \qquad (6) \qquad C = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} \qquad (7)$$

$$K = 10^5 \begin{bmatrix} 12 & -6.84 & 0 \\ -8.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \qquad (8)$$

The MR damper used in this chapter is a small-scale 3000N prototype similar to the one used in Spencer et al. (1997). It is based on a commercially available device. Although small by civil engineering standards, experimental test data and model validation studies are available in the literature (e.g. Pohoryles and Duffour (2015), which could be used to calibrate the model. The input current for the considered damper is 0-1 amp, which is proportional to an applied voltage input of 0-3V. The MR damper and control model used in this chapter have a maximum voltage of 2.25V (0.75 amp) as the experimental data available suggests saturation above this value.

The modified Bouc-Wen model shown diagrammatically in Figure 15 is a general parametric mathematical model that allows general hysteresis behaviours to be simulated. Many previous studies on MR dampers have shown that it can model accurately their hysteretic behaviour (Jansen and Dyke, 2000); therefore, it was chosen in this chapter to simulate the device. The model parameters of the MR damper governing equations are a function of the applied voltage, *u*.

The equations governing the Bouc-Wen system are displayed as follows, according to Dyke et al. (1996):

The MR damping force is calculated from

$$f_{MR} = c_1\dot{y} + k_1(x - x_0) \qquad (9)$$

where $x_0$ is the initial deflection of the spring, $c_1$ is a dashpot that introduces the nonlinear roll-off in the force-velocities loops at low velocities, $k_1$ is a stiffness accumulator, and $\dot{y}$ is the internal velocity of the piston given by:

$$\dot{y} = \frac{1}{c_0 + c_1}\left[\alpha z + c_0\dot{x} + k_0(x - y)\right] \tag{10}$$

Here, the damping observed at high velocities is represented by $c_0$, $x_0$ is the initial displacement of spring $k_1$. The term $k_0$ controls the stiffness in the damper at larger velocities and z is an evolutionary variable to account for hysteresis:

$$\dot{z} = -\gamma\left|\dot{x} - \dot{y}\right|\left|z\right|^{n-1} z - \beta(\dot{x} - \dot{y})\left|z\right|^{n} + A(\dot{x} - \dot{y}) \tag{11}$$

where $A$, $\alpha$, $\beta$, $c_0$, $\gamma$ and $n$ are parameters that give to the hysteresis loop characteristic shape and scale.

The following relationships define the dependence of the force on the voltage applied to the current driver and the resulting magnetic current:

$$\alpha = \alpha_a + \alpha_b u \tag{12}$$

$$c_1 = c_{1a} + c_{1b} u \tag{13}$$

$$c_0 = c_{0a} + c_{0b} u \tag{14}$$

All the '$a$' subscripted variables are obtained considering voltage values equal to 0 V and '$u$' is obtained from the applied command voltage '$v$', and $\eta$, related to the response time of the current driver:

$$\dot{u} = -\eta(u - v) \tag{15}$$

Details on the MR damper parameters used in this simulation are those shown in Table 20. Force-Displacement and Force-Velocity plots of the Bouc-Model were shown in Figure 12.

*Table 20. Bouc-Wen values for the definition of the mechanical model for MR dampers* (Dyke et al., 1996).

| **Physical parameters** | **Value** | **Unit** | **Shape parameters** | **Value** | **Unit** |
|---|---|---|---|---|---|
| $c_{0a}$ | 21 | N·s/cm | $\gamma$ | 363 | cm$^{-2}$ |
| $c_{0b}$ | 3.5 | N·s/(cm·V) | $\beta$ | 363 | cm$^{-2}$ |
| $k_0$ | 46.9 | N/cm | $A$ | 301 | |
| $c_{1a}$ | 283 | N·s/cm | $n$ | 2 | |
| $c_{1b}$ | 2.95 | N·s/(cm·V) | $\eta$ | 190 | s$^{-1}$ |
| $k_1$ | 5 | N/cm | | | |
| $x_0$ | 14.3 | cm | | | |
| $\alpha_a$ | 140 | N/cm | | | |
| $\alpha_b$ | 695 | N/(cm·V) | | | |

A set of 150 unscaled ground motion records from the SIMBAD database (Selected Input Motions for Displacement-Based Assessment and Design (Smerzini et al., 2014), is used as input for the nonlinear dynamic analysis of the case-study structure. SIMBAD includes a total of 467 tri-axial accelerograms, consisting of two horizontal (X-Y) and one vertical (Z) components, generated by 130 worldwide seismic events. The database includes shallow crustal earthquakes with moment magnitudes (M) ranging from 5 to 7.3 and epicentral distances R ≤ 35 km. The specific subset of records considered here provides a statistically significant number of strong-motion records of engineering relevance for the applications presented in this chapter. Those records cover a wide range of magnitudes, source-to-site distance and soil types and are selected by first ranking the 467 records in terms of their PGA values (by using the geometric mean of the two horizontal components) and then keeping the component with the largest PGA value (for the 150 stations with highest mean PGA).

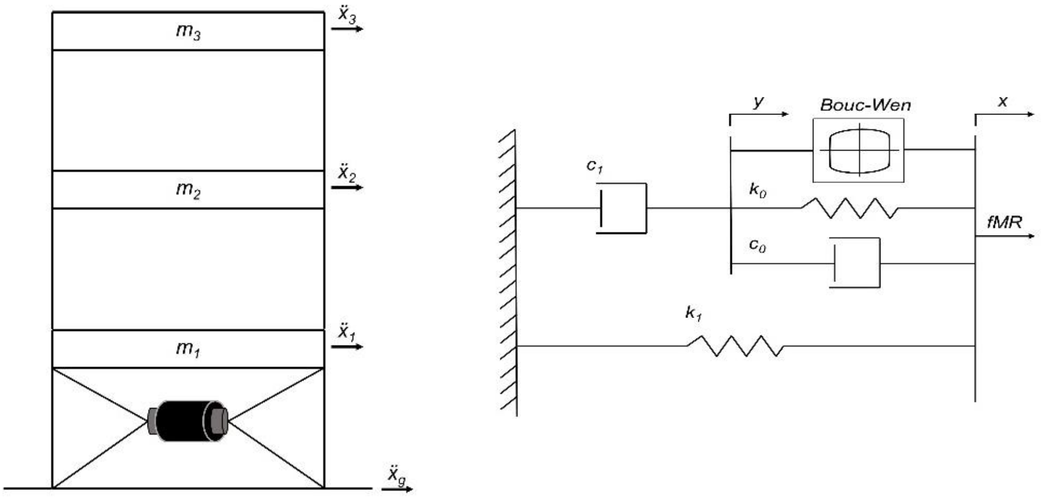


*Figure 15. Case-study structure (left); Modified Bouc-Wen model for MR dampers (right).*

The spectral acceleration at the fundamental period of the hosting structure, $S_a(T_1)$, was the selected IM to calibrate the proposed loss-based control algorithm. To this aim, in each time-history analysis (i.e., for a given ground motion input), the MR damper is fed with a range of voltage values, always keeping the input voltage constant for the duration of the motion. Ten command voltages from 0 V to 2.25 V in 0.25 V steps are considered. Around 1,500 dynamic analyses are performed in total. For each analysis, 9 different EDPs are recorded (for each voltage) and the optimal value of voltage $u_{opt}$ – the one leading to the minimum expected loss as computed using Eq. (5) – is identified. The EDPs considered are: 1) peak displacement (over time) for each storey; 2) peak Interstorey Drift Ratio (over time) for each storey, as the largest difference between the lateral displacements of two adjacent floors, divided by the height of the storey (denoted as $\text{IDR}_i$ for storey *i*-th); and 3) peak acceleration (over time) for each storey (denoted as $\text{PFA}_i$ for storey *i*-th).

Figure 16 shows how the EDPs – IDR at the first storey (Figure 16a) and PFA at the third storey (Figure 16b) vary with the input voltage for two generic ground motion records. As could be anticipated, each EDP has a specific variation with the input voltage so that the voltage value minimizing each EDP is not necessarily the same for all EPDs. From the simulation results obtained, the optimum voltage value in terms of IDR is usually the maximum possible voltage ($u_{max}$) as shown in Figure 16a. However, the dependence of PFA with the input voltage is quite variable and the optimum voltage is strongly IM-dependent as illustrated in Figure 16b. By combining these conflicting demands into a single performance variable, the proposed loss-based approach offers a powerful control tool.

The storey-based approach defined in Eqs. (3-5) requires 1) that the replacement value of the entire building can be distributed among each storey and each type of building components in the structure; and 2) damage functions relating the EDPs to the monetary loss of the entire storey. Regarding point 1), for the case-study building used here, assumptions are made on how the replacement value is distributed among its stories and components. Specifically, it is assumed that the total value is uniformly distributed across all the stories (Ramirez and Miranda, 2009). Each storey's value is distributed into the three categories of components described above assuming the following value breakdown: (1) 0% for drift-sensitive structural components (for simplicity); (2) 50% for drift-sensitive non-structural components; and (3) 50% for acceleration-sensitive components. Regarding point 2), the first step is to define the damage states associated with the component. Definition of damage states is based on the courses of action that need to be taken after observing that damage state in the component. Fragility functions for each category of component are based on HAZUS (Hazards United States – Federal Emergency Management Agency). For illustrative purposes, only one damage state, corresponding to complete damage, is considered for generic non-structural components in office buildings. The fragility functions used for these components are shown in Figure 17a (drift-sensitive) and 6b (acceleration-sensitive).

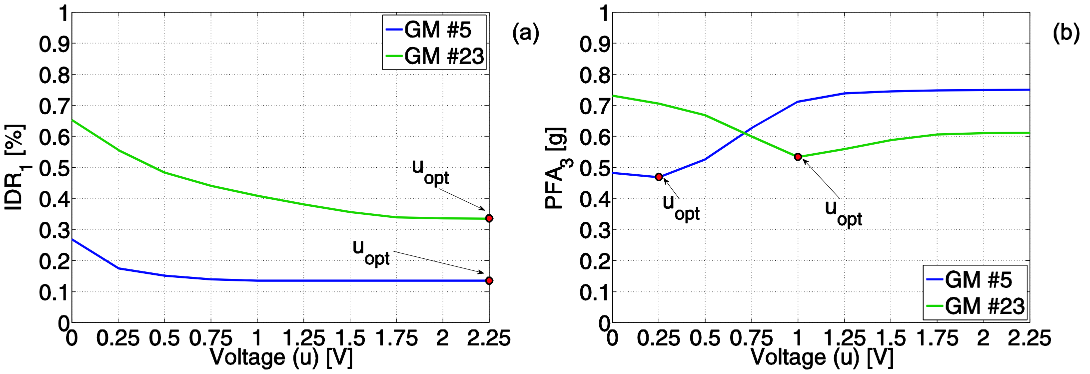


*Figure 16. Example of EDPs vs voltage curves and optimal voltage values for two generic ground motion records: (a) IDR at the first storey; (b) PFA at the third storey.*

Figure 18a shows how the normalized expected loss ratio for two generic ground motion records varies witht the input voltage. From these curves, a single optimum input voltage can clearly be identified and recorded for each ground motion (and associated IM); Figure 18b shows the optimal voltage as function of $S_a(T_1)$. The curve shown is obtained by fitting the cloud of points by robust regression. Each point represents the loss-optimum voltage value for a given ground motion (i.e. IM). This graph is key to calibrate the optimal control algorithm. It shows that for this particular case-study, for events with $S_a(T_1) \leq 0.25$g, the loss-optimum voltage to drive the MR damper is the minimum value (0 V). For 0.25g < $S_a(T_1)$ < 0.7g, the optimum values are fitted to the relationship indicated in the figure, whereas for $S_a(T_1) \geq 0.7$g, the loss-optimum voltage input should be the maximum value (2.25 V).

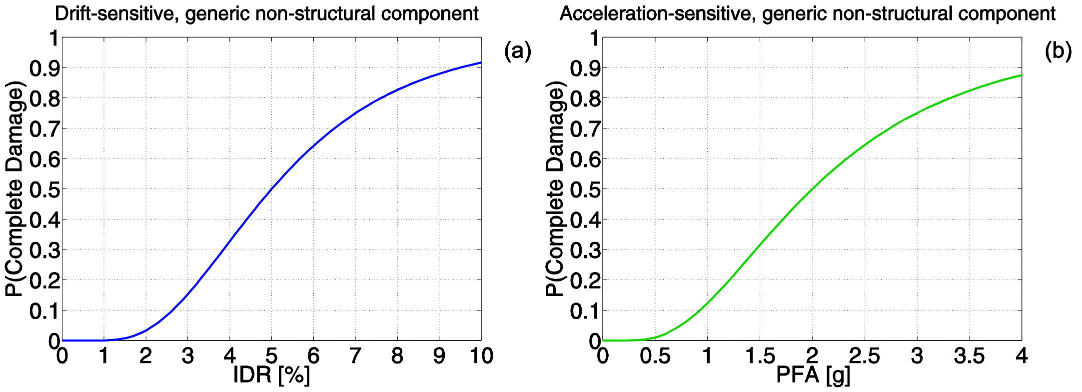


*Figure 17. Fragility functions for complete damage for (a) drift-sensitive, generic non-structural component (in office buildings); and (b) acceleration-sensitive, generic non-structural component (in office buildings).*

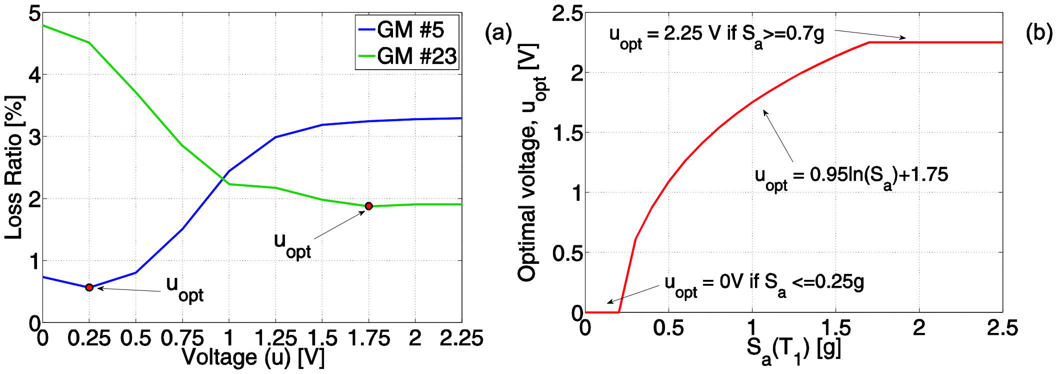


*Figure 18. (a) Example of loss vs voltage curves and optimal voltage values for two generic ground motion records; (b) optimal control algorithm.*

Figure 19 shows the loss ratio in terms of $S_a(T_1)$ for the three different control strategies described in Chapter 4.3. It illustrates how a loss-estimation framework allows control algorithms to be compared. For this case-study, the best performing control strategy (in terms of loss) for all IM is the 'SA+EEW' one (red line). The 'SA ICA' (blue line) is a fairly close second, whereas the passive mode (green line) performs much more poorly. Therefore, the proposed methodology ('SA+EEW') provides the best response of the structure (in terms of losses) compared to the chosen semi-active and passive strategies.

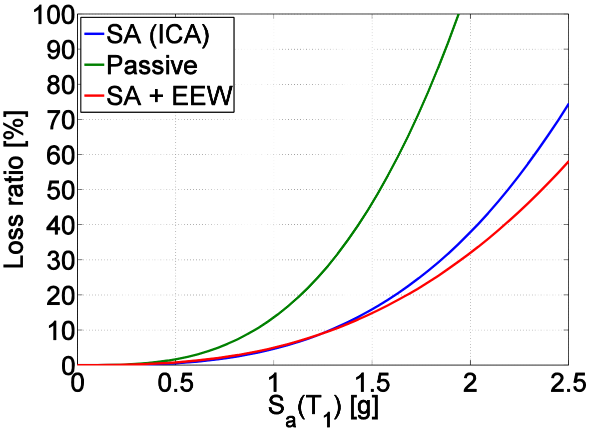


*Figure 19. Comparison of different control algorithms for the case-study structure in terms of loss ratio vs IM.*

## 4.6 Conclusions

This chapter shows how MR dampers can be integrated with an EEW system to control just-in-time the dynamic characteristics of a structure to achieve an optimal response against seismic forces. The “smart-passive” strategy sets the voltage to a constant optimum value for the duration of a given event. It is shown how this optimum value for a given event can be obtained in advance through a calibration process carried out once and for all using ground motion records. These are used as input for nonlinear dynamic analyses of the structure fitted with MR dampers. By varying the input voltage and recording relevant EDPs, the loss associated with a given ground motion and input voltage can be estimated, and the loss-optimum input voltage to the MR damper can be identified.

The methodology is illustrated on a case-study based on a three-floor shear frame fitted with one MR damper between the ground floor and the first floor. It is shown how the loss estimation framework allows an overall optimum voltage value to be identified even though different voltage values can minimize each EDP.

The new SA+EEW strategy is proved to perform better (in terms of losses) against traditional control methodologies, leading to future potential research on the feasibility of the proposed control algorithm.

# Chapter 5. Real-time assessment of building response for EEW applications

## 5.1 Introduction and motivation

The goal of a regional earthquake early warning (EEW) system is to detect earthquakes in the early stages of fault rupture, rapidly predict the intensity/impact of the subsequent ground shaking at various source-to-site distances (i.e., target sites) and warn end users before they experience strong shaking that can potentially cause damage and losses. The most damaging shaking is usually caused by seismic shear (or S-) and surface waves, travelling at about half the speed of the fastest waves (primary waves; or P-waves), and much slower than an electronic warning signal (which travel at nearly the speed of light). EEW systems use P-waves (or early portions of S-waves) to detect strong shaking in the near fault and transmit alerts at target sites/end users ahead of the damaging S-waves (Zollo et al., 2014b). EEW systems can provide up to a few tens of seconds of warning before the arrival of damaging ground shaking at a target site. The warning time (or lead time) depends on the distance to the earthquake rupture (e.g., Wald, 2020). This lead time allows for real-time earthquake risk-mitigating actions, including alerting people to "*drop, cover, and hold-on*" or move to safer locations within/or outside a building (depending on the available warning time), as well as many types of automated actions such as stopping elevators at the nearest floor, opening firehouse doors, slowing rapid-transit vehicles and high-speed trains to avoid accidents/derailments, shutting down gas pipelines to minimize fire hazards, shutting down manufacturing operations to decrease potential damage to equipment, saving vital computer information to avoid data losses, etc. This is not an exhaustive list but rather a snapshot of critical applications that could benefit from EEW (e.g., Porter, 2020). From an earthquake engineering perspective, knowledge that an earthquake may imminently induce severe seismic demand on a target structure (or infrastructure/infrastructure component) enables specific planned mitigating actions (alerting occupants, controlling elevators, etc.) to be taken immediately by relevant end users, for limiting potential losses, particularly in terms of injuries and casualties.

In practice, two fundamental issues related to the concept of/methods employed in EEW restrict its applications: short warning time, particularly close to the rupture, and large uncertainty on the predicted ground-motion field (e.g., Iervolino et al., 2009), which translate in the potential for false and missed alarms. Some EEW applications may lead to a substantial economic loss (e.g., business interruption) if a false alarm occurs (Iervolino et al., 2006). Therefore, deciding whether to take mitigation actions should be based on an advanced probabilistic seismic loss analysis (also accounting for losses due to false alarms) rather than simply using ground-motion Intensity Measures (IM) (e.g., Iervolino et al., 2007). More in general, as the available warning time is short, human intervention would likely take too long for any actions from being activated promptly. Therefore, automated decision and mitigation actions are generally favoured.

A regional EEW system, the focus of this chapter, is based on a dense sensor network covering a geographical area characterized by high seismicity. When an earthquake occurs, the relevant source parameters (event location and magnitude) are estimated from the early portion of recorded signals (initial P- and S-waves) at sensors closest to the rupture. The estimated source parameters can then be used to predict, with quantified confidence, earthquake-induced ground-motion IMs at a distant site where a target structure/infrastructure of concern is located. Specifically, when an event occurs, probabilistic distributions of magnitude (M) and source-to-site distance (R) can be computed in real-time, conditional on some parameters measured in the early portion of the P- (and sometimes S-) waves at a number of near-source stations. For instance, the real-time estimation of the earthquake magnitude is generally based on empirical relationships relating the earthquake size to parameters obtained in the early fraction (3-4 s) of P- and S-wave signals. These parameters are generally associated with the low-frequency content of the ground-motion data, which is sensitive to the seismic moment, and can be related to the maximum amplitude, the dominant frequency, or the energy released by the event (e.g., Cremen and Galasso, 2020, for a comprehensive review of these parameters and related EEW methodologies/models/algorithms). The prediction of different IMs, conditional on those parameters, may be performed by analogy to the well-known framework provided by probabilistic seismic hazard analysis (PSHA; Cornell, 1968) but in real-time (RTPSHA; e.g., Convertito et al., 2008; Iervolino et al., 2006) as formulated in Eq. (16).

$$f_{IM}\left(im \mid \underline{\tau},\underline{s}\right)=\int_{m}\int_{r} f_{IM}\left(im \mid m,r\right)\ f_{M}\left(m \mid \underline{\tau}\right)\ f_{R}\left(r \mid \underline{s}\right)\ dm\ dr \tag{16}$$

where $f_R\left(r \mid \underline{s}\right)$ is the probability density function (PDF) of R conditional on the sequence according to which *n* stations triggered (at a given time *t*), $\underline{s}=\left\{s_1,s_2,...,s_n\right\}$, $f_M\left(m \mid \underline{\tau}\right)$ is the PDF of M conditional on the measures from the n stations triggered (at t), $\underline{\tau}=\left\{\tau_1,\tau_2,...,\tau_n\right\}$, and can be expressed analytically using Bayes' theorem (e.g., Iervolino et al., 2006); $f_{IM}\left(im \mid m,r\right)$ is the PDF of the considered IM conditional on M and R, e.g., from a ground-motion model (GMM). The vector $\underline{\tau}=\left\{\tau_1,\tau_2,...,\tau_n\right\}$ may include any possible parameter estimated from the early portion of recorded signal. The real-time IMs predictions are performed in very uncertain conditions linked to both the real-time estimation of source parameters (e.g., uncertainty in the empirical relationship between M and $\tau$) and the traditional uncertainties involved in PSHA; see Iervolino et al., 2009 for a comprehensive discussion on these issues. Eq. (16) results in real-time-dependent hazard curves, which may be used in a decision-support system for real-time earthquake mitigation action in/at target structures/infrastructures. For instance, a simple decisional rule could consist of issuing the alarm if the probability that a critical IM value for the given asset ($IM_{cr}$) is exceeded at the site (i.e., $Pr\left[IM_{EEW} \geq IM_{cr}\right]$, [where $IM_{EEW}$ is the EEW-based prediction of the considered IM, through Eq. (16)], is larger than a predefined threshold ($P_{cr}$); or alternatively, if the expected value of the predicted IM from the EEW system is larger than $IM_{cr}$ (Iervolino, 2011), i.e., $E\left[IM_{EEW}\right] \geq IM_{cr}$.

For structure-specific applications of EEW, the prediction of structural response in terms of an Engineering Demand Parameter (EDP), such as Interstorey Drift Ratio (IDR) or Peak Floor Acceleration (PFA), rather than the prediction of a ground-motion IM, may be of larger interest and usefulness. This is because, the shaking experienced in mid- to high-rise buildings is generally significantly different from that on the ground and it also differs from one building to another, depending on the building dynamic characteristics. It is also well acknowledged that EDPs are better proxies than IMs for the prediction of earthquake-induced building damage (e.g., Shome et al., 1998).

Therefore, this chapter proposes a set of new empirical prediction equations correlating EDPs for case-study buildings to source- and site-specific parameters (e.g., M, R, and soil type). Based on the newly-proposed equations, Eq. (16) can be modified as in Eq. (17), where $f_{EDP}\left(edp\,|\,m,r\right)$ is the PDF of the considered EDP conditional on M and R, from the proposed empirical models:

$$f_{EDP}\left(edp\,|\,\underline{\tau},\underline{s}\right)=\int_{m}\int_{r} f_{EDP}\left(edp\,|\,m,r\right)\,f_{M}\left(m\,|\,\underline{\tau}\right)\,f_{R}\left(r\,|\,\underline{s}\right)\,dm\,dr \tag{17}$$

In addition, this approach can be extended further to predict the expected loss (or the loss distribution) in a structure conditional on the measures of the seismic sensors, and this would contain the highest level of information for decision making about alarm issuance (e.g., Iervolino et al., 2007).

It is worth noting that an alternative approach to that illustrated in Eq. (17) is to perform Probabilistic Seismic Demand Analysis (PSDA; e.g., Shome et al., 1998), coupling RTPSHA with a probabilistic seismic demand model (PSDM). PSDMs offer a relationship between EPDs and the selected ground-motion IM based on nonlinear analysis of structural response using ground-motion records (e.g., Jalayer and Cornell, 2009) to obtained the conditional distribution of EDP given IM, i.e., $f_{EDP}\left(edp\,|\,im\right)$ though statistical inference methods (e.g., linear regression in the case of *cloud* analysis). However, the proposed approach of Eq. (17) represents a more efficient formulation for the computation of EDPs in real-time, as proposed in this chapter.

The present chapter is organized as follows. First, the simplified building model used in this chapter is introduced. Next, the methodology for the calibration of EDP prediction equations is described, followed by their implementation in an illustrative EEW application. The final section provides some conclusions drawn from the results of the study.

## 5.2 Simplified building model considered in this chapter

Different studies have developed simplified structural models able of accurately estimating lateral displacements of structures subjected to dynamic loadings (e.g., Hoenderkamp and Snijder, 2000; Iwan, 1997; Saiidi and Sozen, 1981). These simplified models can be employed in rapid earthquake response assessment of large building portfolios for the purpose of assessing, at a regional scale, earthquake damage and losses in real time or in the minutes following an event (i.e., near real-time).

One of these simplified models, widely used in several earthquake engineering applications (e.g., Cheng et al., 2014; Cremen and Baker, 2018; Galasso et al., 2013), consists of a flexural cantilever beam coupled with a shear cantilever beam that form an equivalent continuum structure (e.g., Miranda, 1999). Both beams are assumed to be linked by an infinite number of axially rigid members transmitting horizontal forces; therefore, the flexural and shear cantilevers in the combined system are subjected to the same lateral deformation at all heights. Floor mass and lateral stiffness are assumed to remain constant along the height of the building. Modifications for nonuniform mass and stiffness distribution over the height of the building have been proposed in the literature (Miranda and Taghavi, 2005), although those studies concluded that in many cases, using the dynamic characteristics of uniform models could provide reasonable approximations to the dynamic characteristics of nonuniform models.

This conceptual model is a viable tool to approximate the behaviour of real buildings, especially those tall, ranging from moment-resisting frames to shear wall systems, and for which the higher-mode contributions may become important. Moreover, it permits rapidly obtaining estimates of seismic response of multistorey buildings with only three parameters: $T_1$, $\xi$, and α, that are, the fundamental period of the structure, the critical damping ratio at the first mode of vibration, and a non-dimensional quantity controlling the degree of contribution of flexural and shear deformations in the system total deformation, respectively. Figure 20 illustrates the simplified model previously introduced.

Lateral deformations of the equivalent structure are governed by the dimensionless parameter α (Reinoso and Miranda, 2005). Eq. (18) defines the parameter introduced, where H is the height of the building, GA is the shear modulus of the material, and EI is the flexural stiffness of the flexural beam.

$$\alpha = H\sqrt{\frac{GA}{EI}} \tag{18}$$

By modifying the value of the dimensionless parameter α, the contributions of the flexural and shear beams to the overall lateral deformation of the equivalent structure are controlled. Consequently, low values of α, particularly close to zero, correspond to purely flexural-type deformation structures, while large values of α, larger than 8, represent shear-type deformed shapes of the structure. Dual systems could then be defined with values of α between 2 and 8, where contributions from both systems can be represented.

To illustrate the impact of changing the value of α, the curves in Figure 21 show the normalised fundamental modal shapes and corresponding interstorey drift as a function of the nondimensional height $z = x/H$, for $\alpha$ equal to 0.1, 8 and 30. By simulating a structure that behaves as a flexural cantilever beam ($\alpha = 0.1$), or as a buildings where lateral shear deformations predominate over lateral flexural deformations ($\alpha = 30$), the peak interstorey drift occurs at large heights or near the ground storey, respectively. In addition, a schematic representation of the impact that different values of $\alpha$ have in structural response (in terms of deformation shapes) is shown in Figure 22.

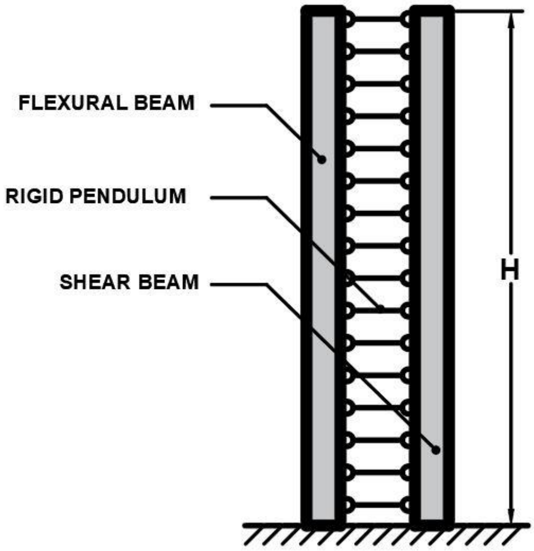


*Figure 20. Simplified continuous model used in this study.*

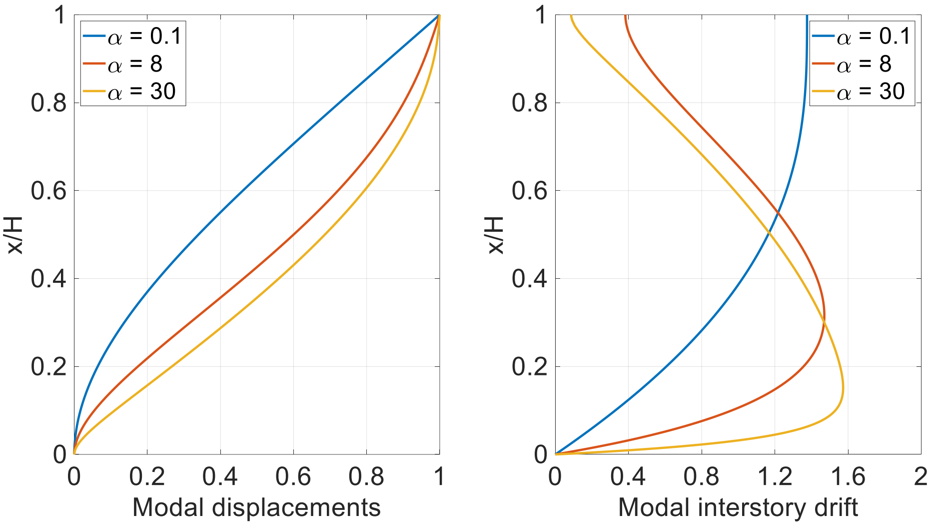


*Figure 21. Dependence of the lateral deformation (in terms of modal displacement and modal interstorey drift) on α for the first mode of vibration.*

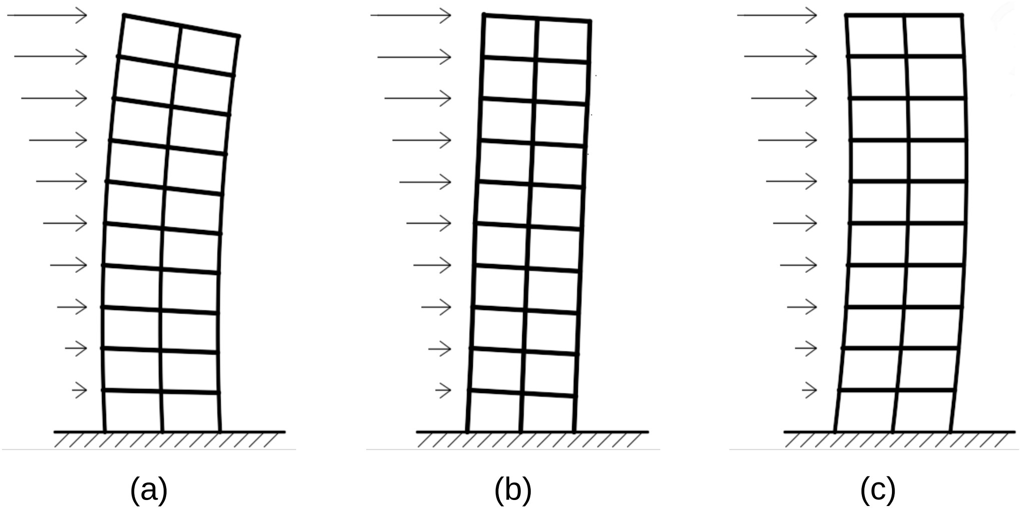

(a) (b) (c)

*Figure 22. Lateral deformations for the simplified continuous model proposed by* (Miranda and Akkar, 2005)*: (a) flexural-type deformation; (b) combined flexural-shear deformations; (c) shear-type deformation*

Previous studies have provided closed-form/analytical solutions of the fourth-order partial differential equation describing the combined shear and flexural beams for: (1) lateral static loading to approximate the maximum roof and interstorey drift demands of first-mode dominated structures (e.g., Miranda, 1999); (2) computing the approximate dynamic structural behaviour (in terms of lateral displacements and peak floor accelerations) by using up to the first three modes of vibration and real records (e.g., Miranda and Taghavi 2005); and (3) estimating generalized drift spectrum (e.g., Miranda and Akkar, 2006). Evaluation of the results presented in the previously mentioned studies indicates that this analysis tool provides relatively accurate results not only in terms of peak values of response parameters but also, in general, in terms of response histories.

In particular, assuming uniform mass and uniform stiffness along the height of the structure, Miranda and Akkar (2006) and Reinoso and Miranda (2005) derived analytical functions for the computation of Interstorey Drift Ration (Eq. 19), Generalized Interstorey Drift Ration (Eq. 20) and Peak Floor Acceleration (Eq. 21):

$$IDR(j,t) \approx \frac{1}{H}\sum_{1}^{m}\Gamma_i \varphi'_i(x) D_i(t) \tag{19}$$

where $IDR(j,t)$ is the Interstorey Drift Ration at the *j*-th storey, at time *t*, *m* is the number of modes of vibration, $\Gamma_i$ is the modal participation factor corresponding to the *i*-th natural mode, $\varphi'_i(x)$ is the first derivative of the mode shape $\varphi_i(x)$, and $D_i(t)$ is the displacement of a single degree of freedom system, characterised by its own natural frequency $\omega_I$ and the modal radio $\zeta_i$.

$$IDR_{max} = \max_{\forall t,x} \left| \frac{1}{H} \sum_{1}^{m} \Gamma_i \varphi'_i D_i(t) \right| \tag{20}$$

where $IDR_{max}$ is the maximum IDR computed along the normalized height of the structure, defined as Generalized Interstorey Drift Ration (GIDS).

$$PFA(x,t) \approx \left[ 1 - \sum_{1}^{m} \Gamma_i \varphi_i(x) \right] \ddot{u}_g(t) + \sum_{1}^{m} \Gamma_i \varphi_i(x) A_t(t) \tag{21}$$

where $PFA(x,t)$ is the Peak Floor Acceleration at time *t* and at normalized height *x*, $A_t(t)$ is the absolute acceleration time history of a single degree of freedom system, and $\ddot{u}_t(t)$ is the acceleration time history of the input ground motion.

The most notable limitations of the simplified model are related to assuming a linear elastic behaviour and a classical damping in the building. Hence, the method is aimed at the estimation of seismic demands at performance levels corresponding to elastic behaviours, with very limited levels of nonlinearity.

### 5.2.1 Description of the considered systems and demand measures

In order to investigate the dynamic response of a wide range of simplified building models, a number of continuum systems as described above are selected, including: (1) 15 (fundamental) oscillation periods ($T_1$), between 0.1s and 5s; (2) three shear to flexural deformation ratios ($\alpha$) to represent respectively shear walls structures ($\alpha$ = 0.1), dual systems ($\alpha$ = 8), and moment-resisting frames ($\alpha$ = 30); (3) the normalised height (z) of the simplified model has been discretised in 101 points, considering a step between points equal to 0.01. The period range is sampled with a 0.1s step from 0.1s to 0.5s, with a step of 0.25s between 0.5s and 1s, and with a step of 0.5s between 1s and 5s. Two approximations for the analysis are considered: (1) equal damping ratios of 5% for all modes; (2) only the first six modes of vibration are taken into account so that the sum of their effective modal masses contains more than 90% of the system total mass (Reinoso and Miranda, 2005).

Three main EDPs are considered in the chapter: the peak (over time) IDR, defined as the difference in lateral displacements between two consecutive floors normalized by the interstorey height; the maximum (over all stories) peak inter-storey drift ratio (denoted as MIDR); and PFA. These EDPs have demonstrated to be well correlated to both structural and non-structural damage, which contribute a major share of the total loss in an earthquake.

It is worth noting that, for a given value of $T_1$, the total height of the model is computed using the relationship (in metric units) suggested for steel moment-resisting frames in ASCE 7-16 (ASCE, 2016), Eq. (22).

$$T_1 = 0.0724H^{0.8} \rightarrow H = \sqrt[0.8]{\frac{T_1}{0.0724}} \tag{22}$$

where H is the height of the building (in meters) and $T_1$ is the structure’s period of oscillation.

A series of MATLAB® scripts has been developed by the author to implement the closed-form/analytical solutions for the fourth-order partial differential equation describing the considered model.

## 5.3 Calibration of the proposed prediction equations

The methodology followed to calibrate the proposed EDP prediction equations for case-study building models consists of performing nonlinear regression to establish empirical models between earthquake and site features (i.e., M, R, soil type) and each selected EDP, particularly IDR and PFA. The main steps of the methodology implemented here are introduced in the following sub-sections.

### 5.3.1 Ground motion database selection

A subset of two-component ground-motion records from the Italian Accelerometric Archive (or ITACA v1.0; Pacor et al., 2011 – as implemented in REXEL 3.5; Iervolino et al., 2010) is used as input for the numerical simulations of the simplified building model described above.

ITACA (version 1.0) includes a total of 3,995 three-component accelerograms, consisting of two horizontal (X-Y) and one vertical (Z) components, generated by about 1,800 earthquakes located in Italy between the 1972 and 2009. The database mainly includes events associated with normal faults, with magnitude up to 6.9 (based on local magnitude for events smaller than 4, and moment magnitude for stronger events), and recording sites characterized by epicentral distances within 200 km (with a large portion of records within 100 km). For the soil classification of the recording sites, the Eurocode 8 (or EC8 - European Commitee for Standardization, 2004) classification is considered, consisting of five soil types (A,B,C,D,E) on the basis of the average value of the shear wave velocity within the first thirty meters of soil deposit at the site.

Within the scope of the present chapter, 589 two-component records from 39 events have been selected, considering free-field records corresponding to earthquake moment magnitude equal or greater than 5 and epicentral distance equal or less than 200km; 49% of the selected ground-motions were caused by the rupture of normal faults, 33% by thrust faults, and 18% by strike-slip faults. 46% of the recording stations were situated in soil class A (rock), 29%

in soil class B (very stiff clay), 17% in soil class C (stiff clay), and the remaining 8% in soil classes D and E (soft and alluvium). Figure 23 shows the distribution of the selected records in relation to magnitude and epicentral distance ($R_{epi}$), while Figure 24 illustrates the number of records corresponding to their respective M and $R_{epi}$. $R_{epi}$ has been selected for this chapter upon more accurate distance metrics, such as Joyner Boore ($R_{JB}$) or Rupture Plane ($R_{RUP}$), as the computation in real-time of $R_{epi}$ is faster, allowing for larger lead times provided by an EEW system. Additionally, the calculation of $R_{JB}$ and $R_{RUP}$ require information relevant to the extent of the fault rupture in real-time, which is a feature that is still in development and currently available in few EEW systems worldwide (Cremen and Galasso, 2020).

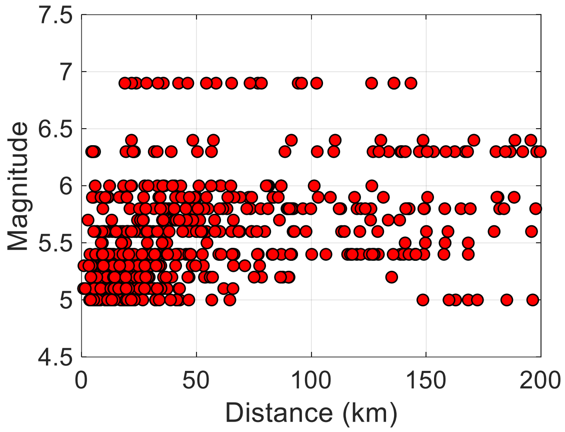


*Figure 23. Distribution of selected records with respect to magnitude and epicentral distance.*

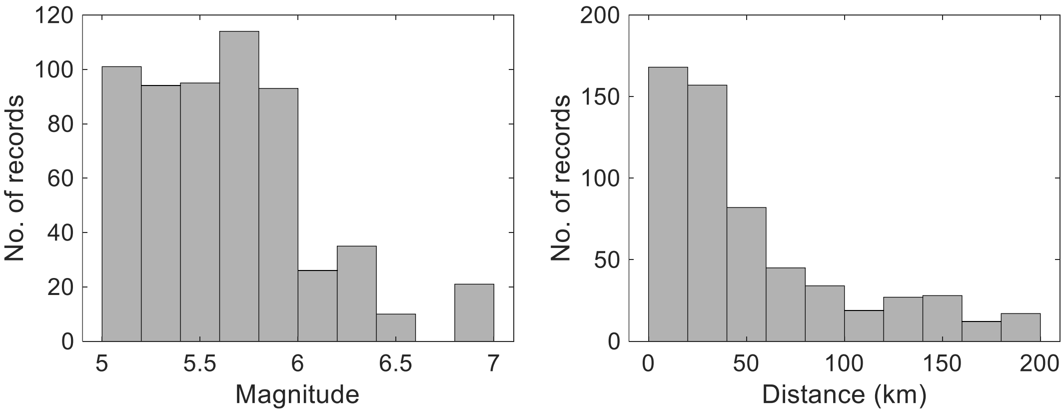


*Figure 24. Histograms of M and R (589 GMs).*

### 5.3.2 Model specification and estimation algorithm

Nonlinear regression analysis is carried out for the calibration of the proposed EDP prediction equations. To this aim, the first step is to define the model specification, i.e., the selection of the functional form to represent the output from the structural simulations as a function of the considered explanatory variables.

As the new prediction equations are going to be integrated in an EEW framework, real-time (EEW-based) predictions of the explanatory variables considered in the proposed functional form need to be available, based on a given EEW algorithm. In addition, a simple and efficient functional form should be selected, mainly for two reasons: 1) in an EEW context, longer computation times reduce the available lead time for the implementation of mitigation actions; 2) As explained in section 5.2, EEW systems (regional) generally estimate only earthquake source parameters and ground shaking, the systems do not usually estimate information such as type of faulting. Therefore, a functional form that depends on the style of faulting is not within the scope of this chapter, and the parameters of preference herein are only earthquake magnitude, epicentral distance and soil type.

Based on these considerations, the functional form selected in this chapter is the same of the GMM for Italy proposed by Bindi et al. (2009), adapted from the functional form introduced by Sabetta and Pugliese (1996). The selected functional form is shown in Eq. (23); it relates the geometric mean of each considered EDP (dependent variable) to the independent variables of magnitude (M), Epicentral Distance ($R_{epi}$), and soil amplification ($F_S$), as follows:

$$log_{10} Y = b_1 + b_2 \cdot M + b_3\, log_{10} \sqrt{{R_{epi}}^2 + b_4^2} + b_5 S_s + b_6 S_A + \varepsilon\sigma \tag{23}$$

In Eq. (23), $Y$ is the EDP of interest (MIDR, IDR or PFA) dependent of the values of $T_1$ and $\alpha$ (and z, for PFA); $b_1, b_2, b_3, b_4$ are the regression coefficients;

M is the moment magnitude, R is the epicentral distance (in km); $S_S$ and $S_A$ are dummy variables taking into account site effects and assuming the value of 1 for stiff and soft types of soil, respectively, and zero otherwise; and $\varepsilon\sigma$ is the resulting fractional number of standard deviations.

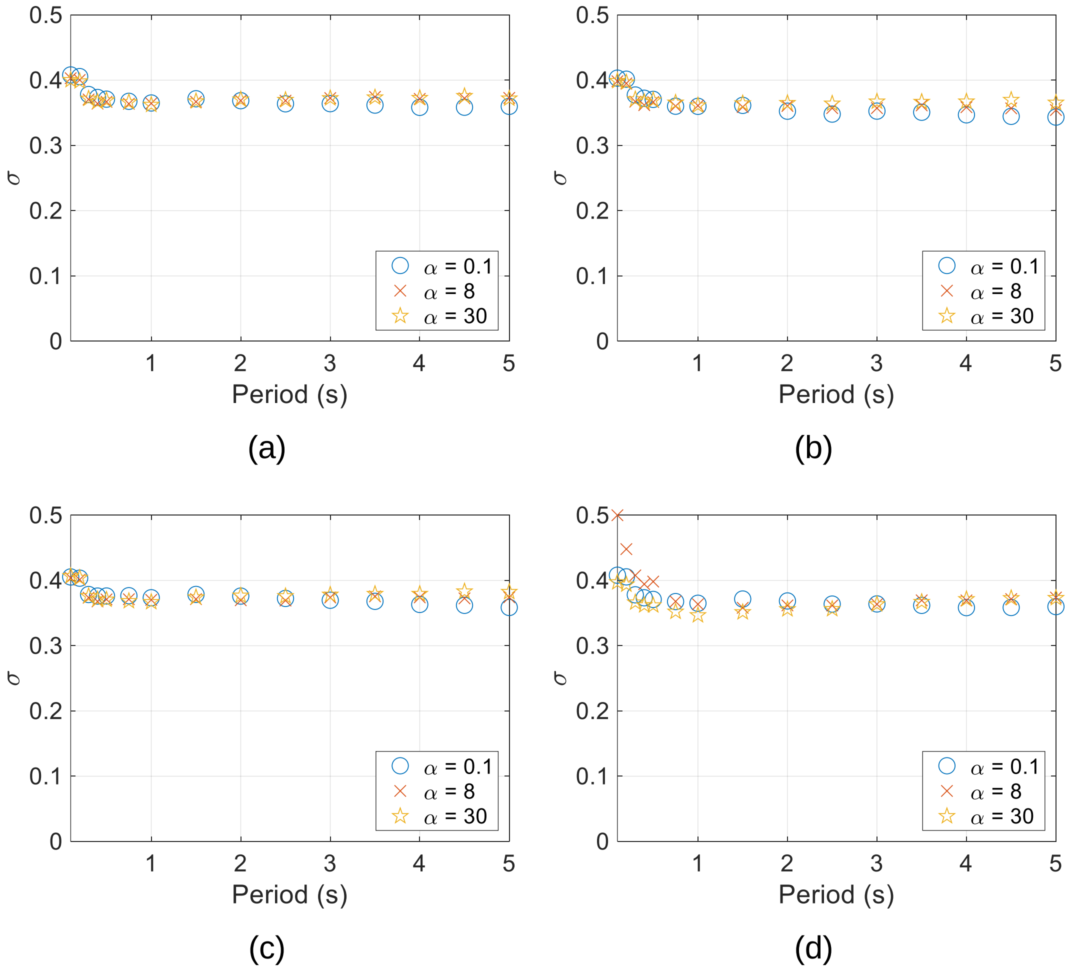
## 5.4 Results and discussion

The estimates for the regression coefficients for MIDR, IDR and PFA prediction equation have been obtained by using a nonlinear least-squares regression algorithm implemented on Matlab®. The corresponding values of the coefficients, together with the estimated standard deviations of the residuals (or root-mean-square errors) can be found in Appendix #1.

The calibration of the regressions is evaluated by analysing statistical parameters obtained from the model, such as the root-mean-square-errors and the multiple correlation coefficient ($R^2$). For example, the variation of the standard deviation values versus the fundamental period is analysed for each EDP and different values of $\alpha$. Figure 25a shows the standard deviation associated with MIDR. Figure 25b, Figure 25c, and Figure 25d present the standard deviation associated with IDR (z=0.05), IDR (z=0.30), and IDR (z=1.00), for three different values of $\alpha$ (0.1, 8, and 30). Figure 25e and Figure 25f illustrate the standard deviation associated with PFA(z=0.50) and PFA(z=1.00). In general, the standard deviation plots in Figure 25 display a stable trend for fundamental periods larger than 1s with an average value of 0.35. These results suggest that the standard deviation is not affected by fundamental periods or by the selected values of the lateral stiffness ratio. In a similar work, Neam and Taghikhany (2016) derived a new prediction equation for MIDR considering near-fault ground motions, where larger values of standard deviations (0.5 to 0.6) were obtained.

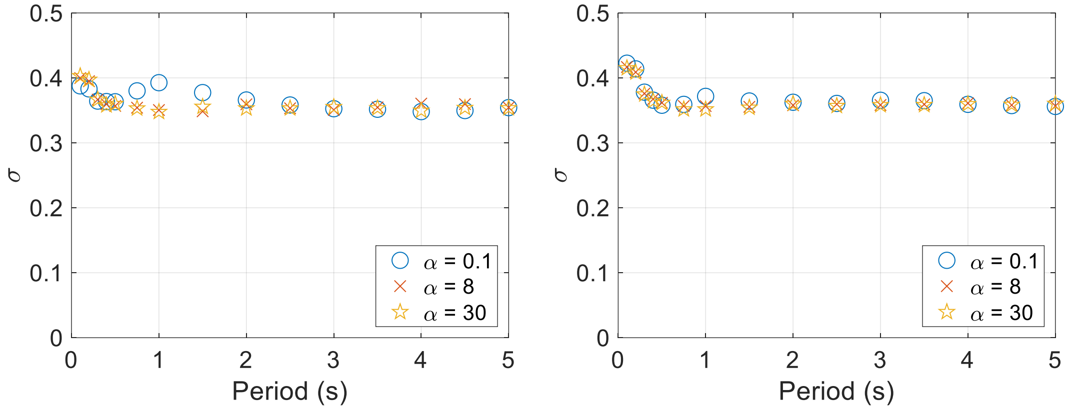
Figure 26 and Figure 27 illustrate the distribution of residual values against M and R, corresponding to a structure with natural period $T_1 = 0.75$ s and MIDR ($\alpha = 8$), IDR (z=1.00, $\alpha = 8$), and PFA (z=1.00, $\alpha = 30$). A careful analysis of the graphs allows to conclude that the scatter plot is equally and randomly spread across the horizontal axis (Residual = 0), throughout the range of fitted values. Similar patterns have been also found for the rest of periods and heights of the simulated structures, which suggests that the derived equations have produced unbiased estimates.

Another statistical measure obtained from the regression analyses is the coefficient of determination ($R^2$), which measures the proportion of variance in the response that is explained by the regression. The average $R^2$ values of the regressions in this chapter are in the range of 70 to 75%, which suggests an acceptable fit of the data.



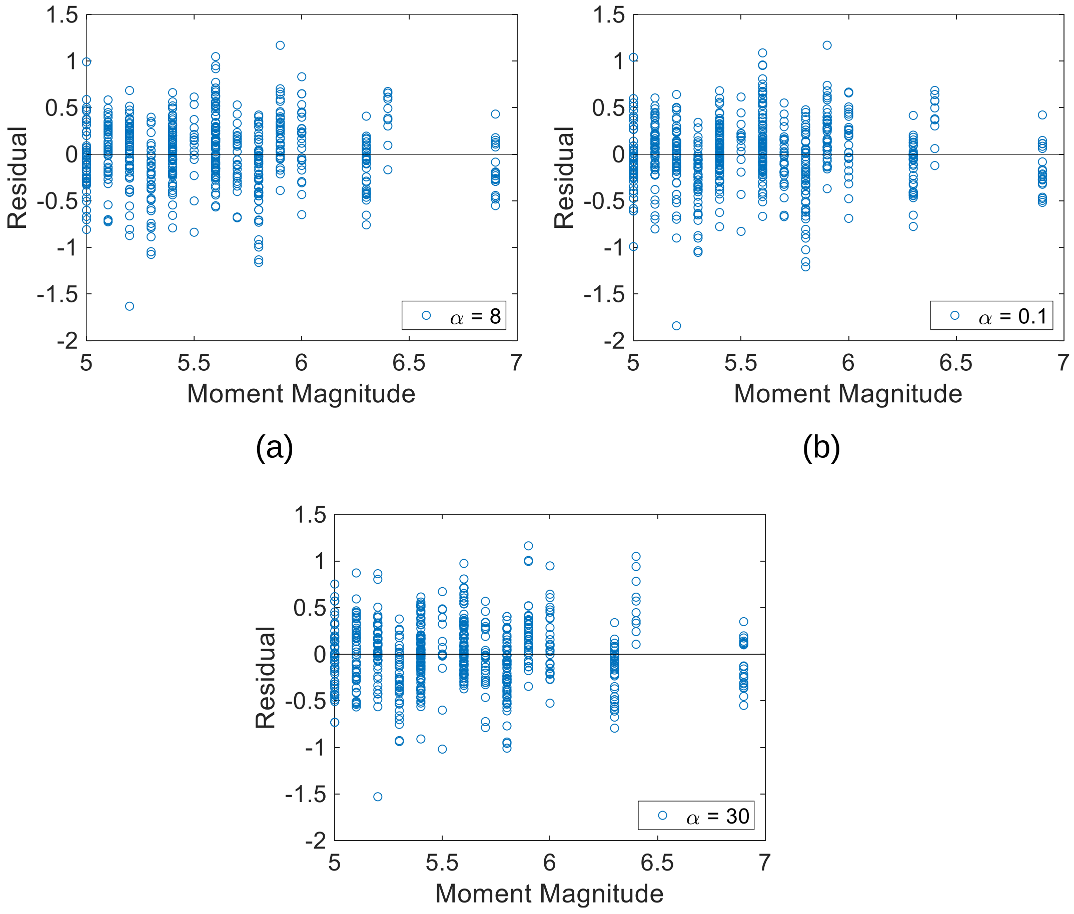
(a) (b)

(c) (d)



(e) (f)

*Figure 25. Standard deviations of (a) MIDR, (b) IDR (z=0.05), (c) IDR (z=0.30), (d) IDR (z=1.00), (e) PFA (z=0.50), and (f) PFA (z=1.00), for three values of lateral stiffness ratio. Functional form proposed by Bindi et al. (2009).*

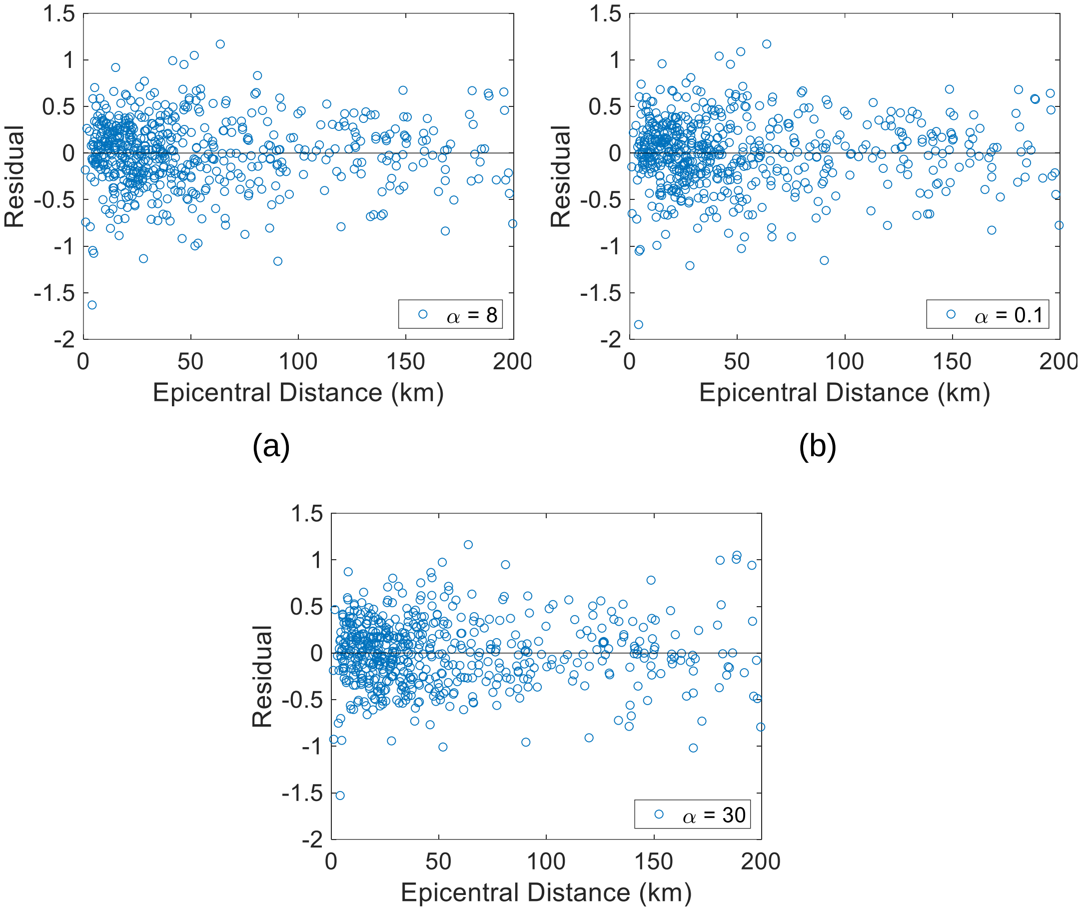


(a) (b) (c)

*Figure 26. Moment Magnitude vs Residual plots for (a) MIDR, (b) IDR (z=1.00), and (c) PFA (z=1.00). All cases are computed adopting a period T1 = 0.75 s.*

The values of the root-mean-square errors , the residual plots, and the coefficients of determination indicate a good agreement in the estimation of

MIDR, IDR, PFA., which demonstrates that the new developed equations can be implemented in the following sections of the chapter.



(a)

(b)

(c)

*Figure 27. Epicentral Distance vs Residual plots for (a) MIDR, (b) IDR (z=1.00), and (c) PFA (z=1.00). All cases are computed adopting a period T1 = 0.75 s.*

### 5.4.1 Performance of the predictive models in comparison to the simplified model

This section presents a series of comparisons (in terms of MIDR, IDR and PFA) between the results obtained through the new predictive models and the “observed” response of the considered case-study structures computed by implementing the simplified model described in section 5.2, under historical ground motions.

The comparison was carried out for a single fundamental period, $T_1$ = 0.75 s, and for three values of alpha (0.1, 8 and 30).Three strong earthquakes (Mw

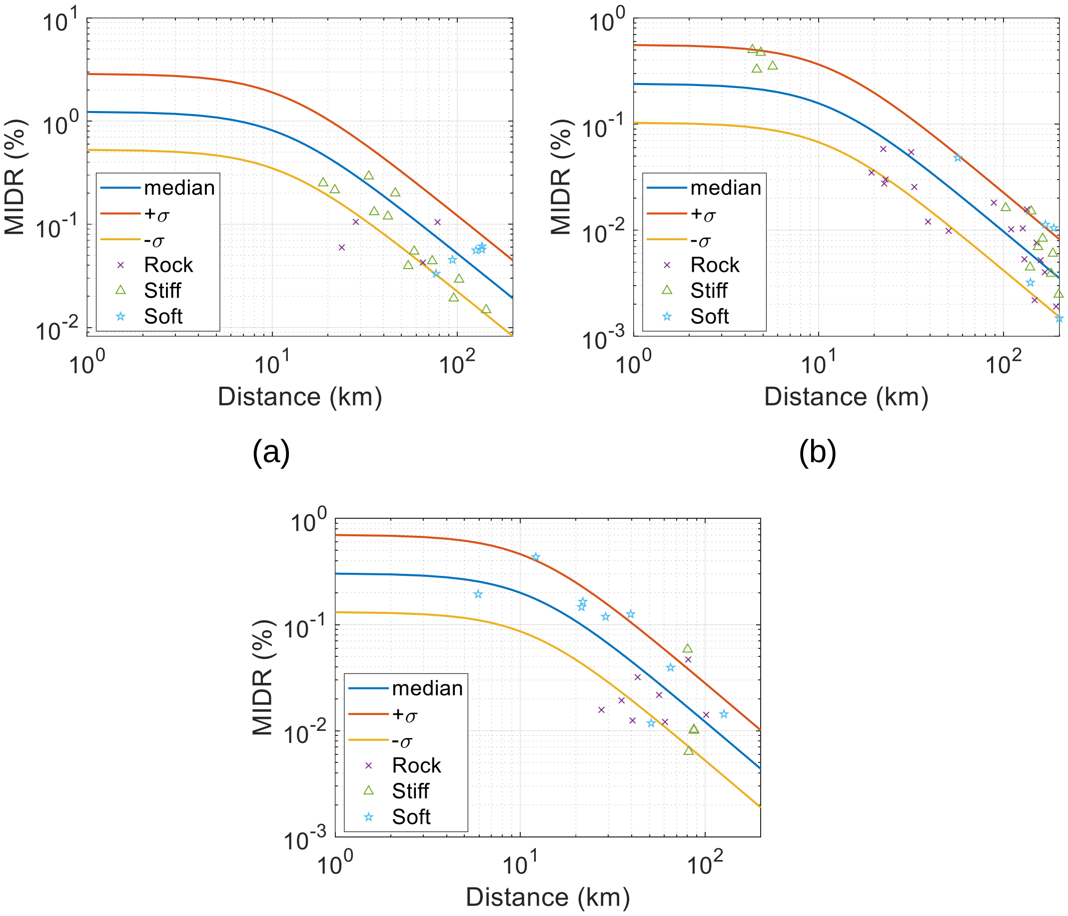
>= 6) were selected from the 39 set for the testing of the predictive models, considering different types of soil classes to illustrate soil effects in the computation of the EDPs.: $M_w$ 6.9 1980 Irpinia Earthquake, stiff soil, $M_w$ 6.3 2009 L'Aquila earthquake, rock soil, and $M_w$ 6.0 1997 Umbria-Marche earthquake, soft soil.

Figure 28, Figure 29, and Figure 30 show the comparison (for MIDR, IDR and PFA) of the building response predicted by the new predictive models and the response of the structures subjected to historical seismic events. As a general trend, the plots clearly show that most of the computed historical response data fall within the region defined by the +/- one standard deviation, corroborating again the precision of the new predictive equations.

In addition, it can be noted that the observed values of MIDR, IDR and PFA are located in the area increased by one standard deviation for short and long epicentral distances, suggesting that the models are able to capture with good agreement the distance variability.

Moreover, the models' estimations do not seem to be affected by the variation of values of alpha. The values of z and alpha selected herein tend to result in peak demands of IDR and PFA in the structure (e.g., large values of alpha usually derive in peak IDR demands at low heights of the structure), however the model captures such peaks within the envelope formed by the standard deviations.

Finally, the plots illustrate that the gaps between the computed responses associated with a given soil type and median trend relative to that soil type are generally shorter than those observed when other soil typologies are assigned. The majority of outliers in Figure 28, Figure 29, and Figure 30, are those points in which the event's soil conditions are different to those of the sensors that recorded such event, suggesting that the prediction models tend to be considerably sensitive to soil conditions.



(a)

(b)

(c)

*Figure 28. Prediction equation in terms of MIDR vs historical data. T1 = 0.75 s, (a) 6.9 Mw Irpinia earthquake (stiff conditions, $\alpha$ =0.01), (b) 6.3 Mw L'Aquila earthquake (rock conditions, $\alpha$ =30), (c) 6.0 Mw Umbria-Marche earthquake (soft conditions, $\alpha$ =8)*

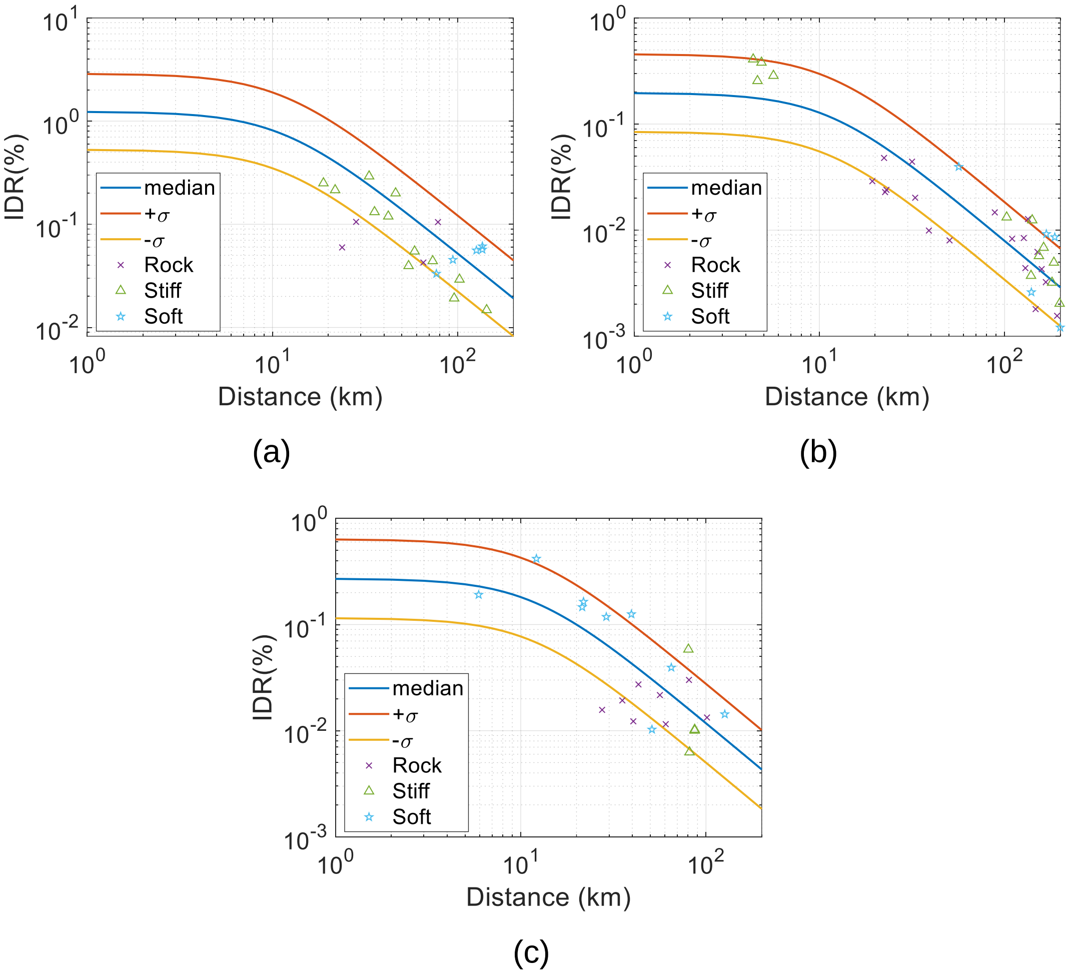
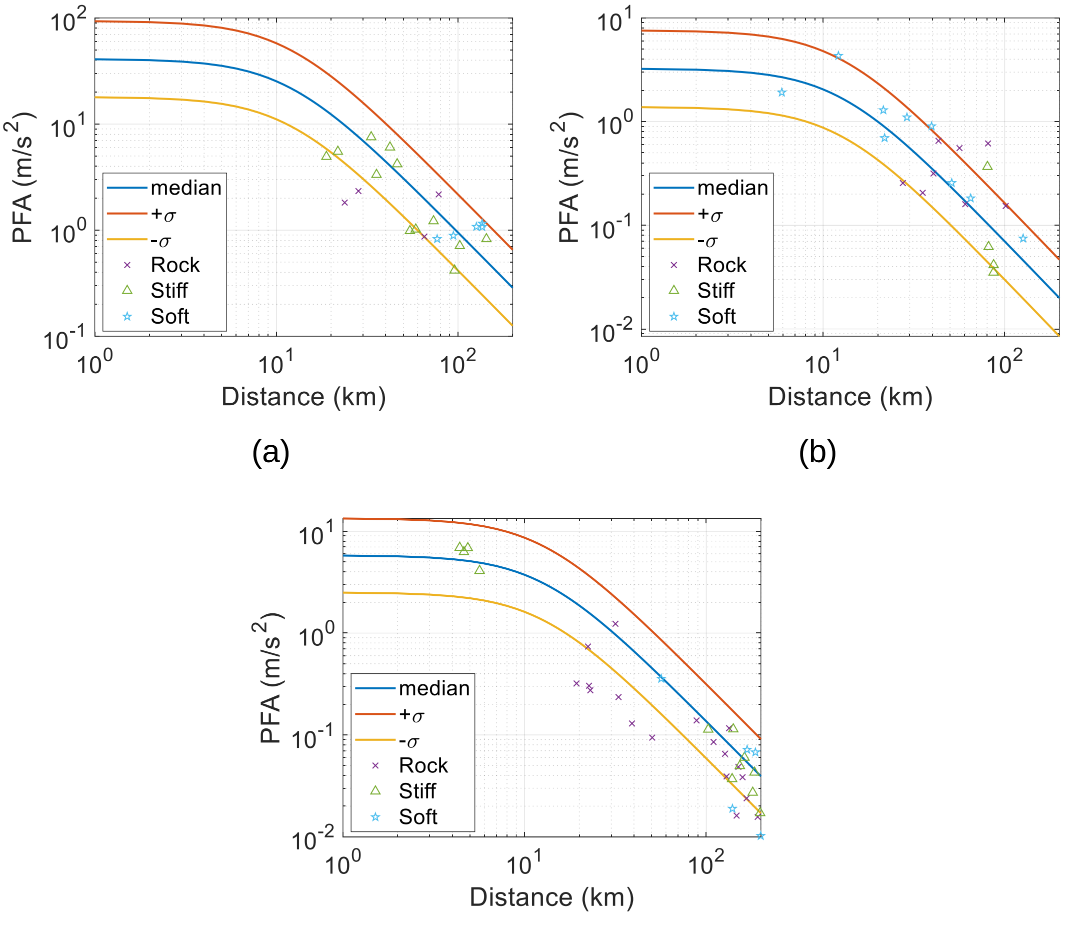


*Figure 29. Prediction equation in terms of IDR vs historical data. T1 = 0.75 s, (a) 6.9 Mw Irpinia earthquake (stiff conditions, $\alpha$ =0.01, z=1.00), (b) 6.3 Mw L'Aquila earthquake (rock conditions, $\alpha$ =30, z=0.05), (c) 6.0 Mw Umbria-Marche earthquake (soft conditions, $\alpha$ =8, z=0.30).*



(a)

(b)

(c)

*Figure 30. PFA Prediction equation in terms of PFA vs historical data. T1 = 0.75 s, (a) 6.9 Mw Irpinia earthquake (stiff conditions, $\alpha$ =0.01, z=1.00), (b) 6.3 Mw L'Aquila earthquake (rock conditions, $\alpha$ =30, z=0.05), (c) 6.0 Mw Umbria-Marche earthquake (soft conditions, $\alpha$ =8, z=0.30).*

## 5.5 Real-time application of the proposed prediction equations for EEW applications in the Campania region, Italy

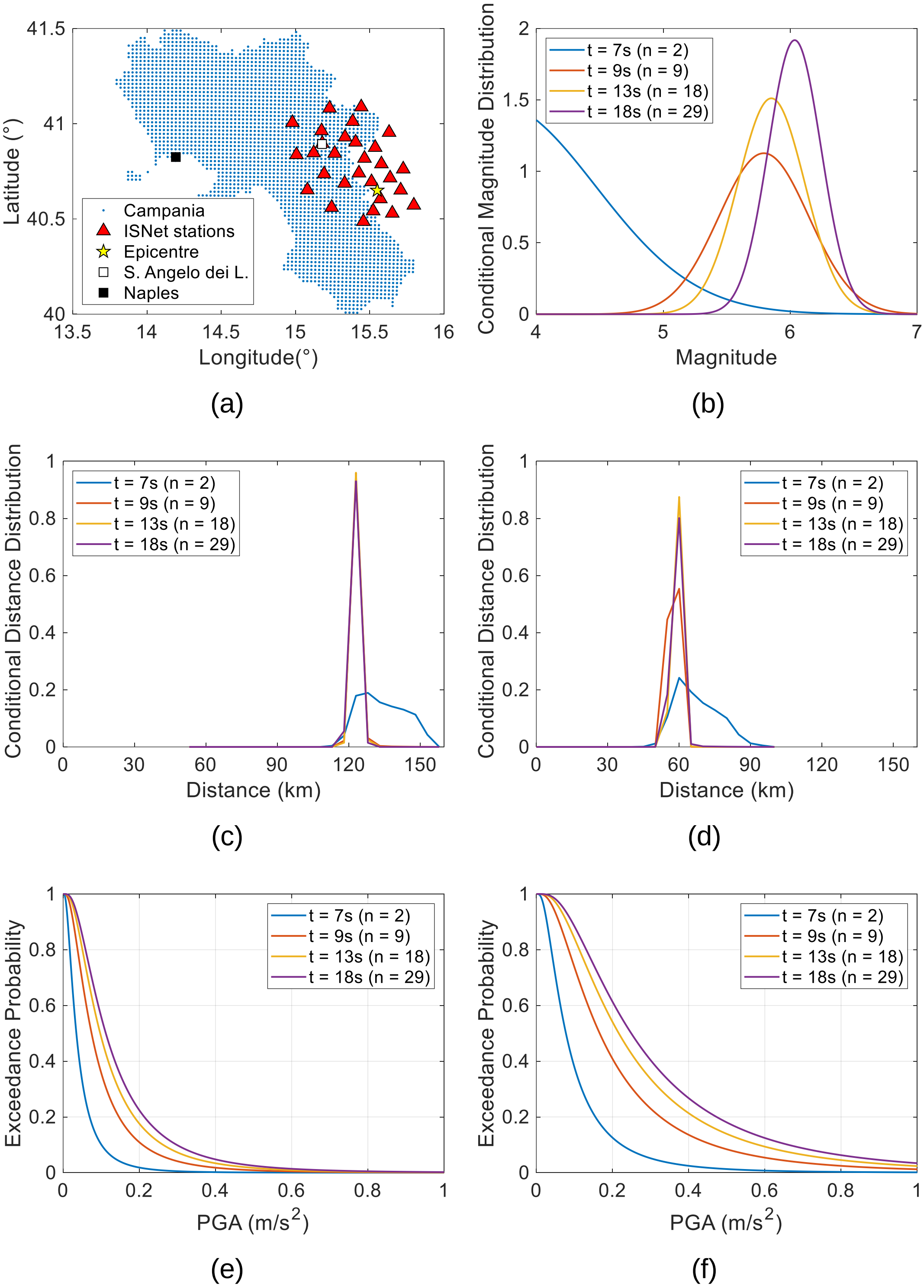
This section describes an actual application for RTPSHA of equation (16), but in terms of EDPs (Eq. 17). The simulation of a $M_w$ 6 earthquake with epicentre in the Campania region (Italy), is adopted for the computation of building response, in particular urbanised areas of the aforementioned region. The dominant network that provides estimates of magnitude and epicentral distances for Campania is ISNet, consisting of 29 seismic networks deployed in the region that are all equipped with EEW capability. Originally, the simulation of the event has been implemented by Iervolino et al. (2009), who focused on the real-time hazard analysis in terms of PGA for the cities of

Naples, located 124km away from the epicentre of the earthquake, and S. Angelo dei Lombardi, which is located 60km away.

Figure 31b illustrates the evolution of the predicted magnitude distribution when sensors detect the arrival of P- waves. Four instants of time after the earthquake’s origin have been considered, namely t = 7s, t = 9s, t = 13s and t = 18s, corresponding to 2, 9, 18 and 29 seismic sensors of the network progressively triggered. It is worth noting that the first estimate, after 7 s from the origin of the event (when only 2 stations have detected the earthquake), underpredicts the magnitude value since it is mainly based on the *a priori* probabilistic distribution (which assigns higher probability of occurrence to small-scale events) as Iervolino et al. (2006) observed. Gradually, as more stations are triggered, the prediction becomes stable and closer to the actual value selected.

The source-to-site distance estimation is derived from the triggering sequence of stations, taking into account the P- wave velocity. Figure 31c and Figure 31d show the evolution of the probabilistic distribution of distance, for the sites in Naples and S. Angelo dei Lombardi respectively, as time passes. A few seconds after the earthquake’s origin, these distributions are already stable and centred on the actual values of source-to-site distance (124 km for Naples and 60 km for S. Angelo dei Lombardi).

Figure 31e and Figure 31f illustrate, for the locations of Napoli and S. Angelo dei Lombardi respectively, the evolution of the exceedance probability of PGA. Clearly, the curves obtained attain higher values in the case of S. Angelo dei Lombardi since this site is characterised by a predicted source-to-site distance much shorter than that one for Naples.

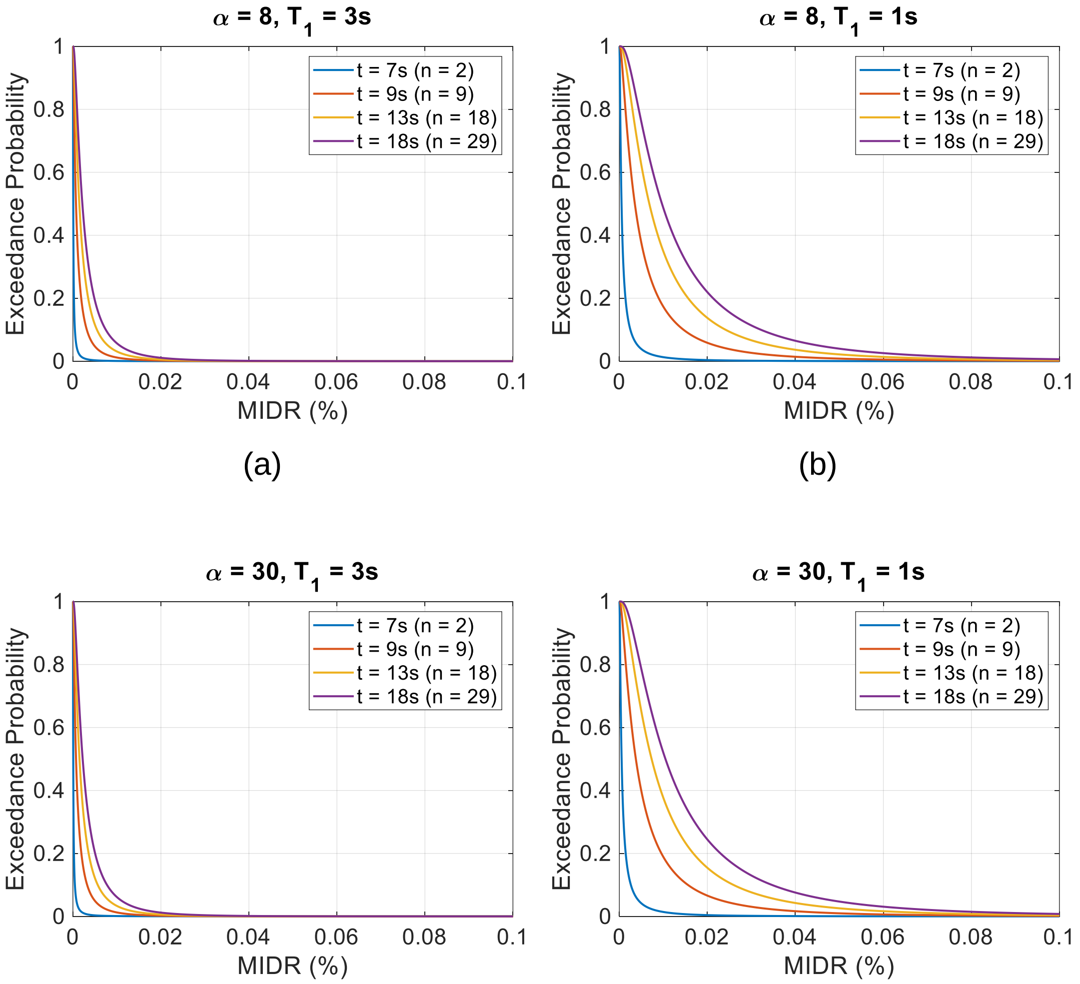


(a) (b) (c) (d) (e) (f)

*Figure 31. Simulation of a M6 earthquake occurring in the region covered by the ISNet network and results for a site in Naples (left hand side) and S. Angelo dei Lombardi: (a) map of the Campania region showing the ISNet network, the two locations and the epicentre; (b) evolution of the probabilistic magnitude distribution; (c), (d) evolution of the probabilistic distribution of source-to-site distances at the two locations; (e), (f) evolution of the predicted exceedance probability of PGA at both locations.*

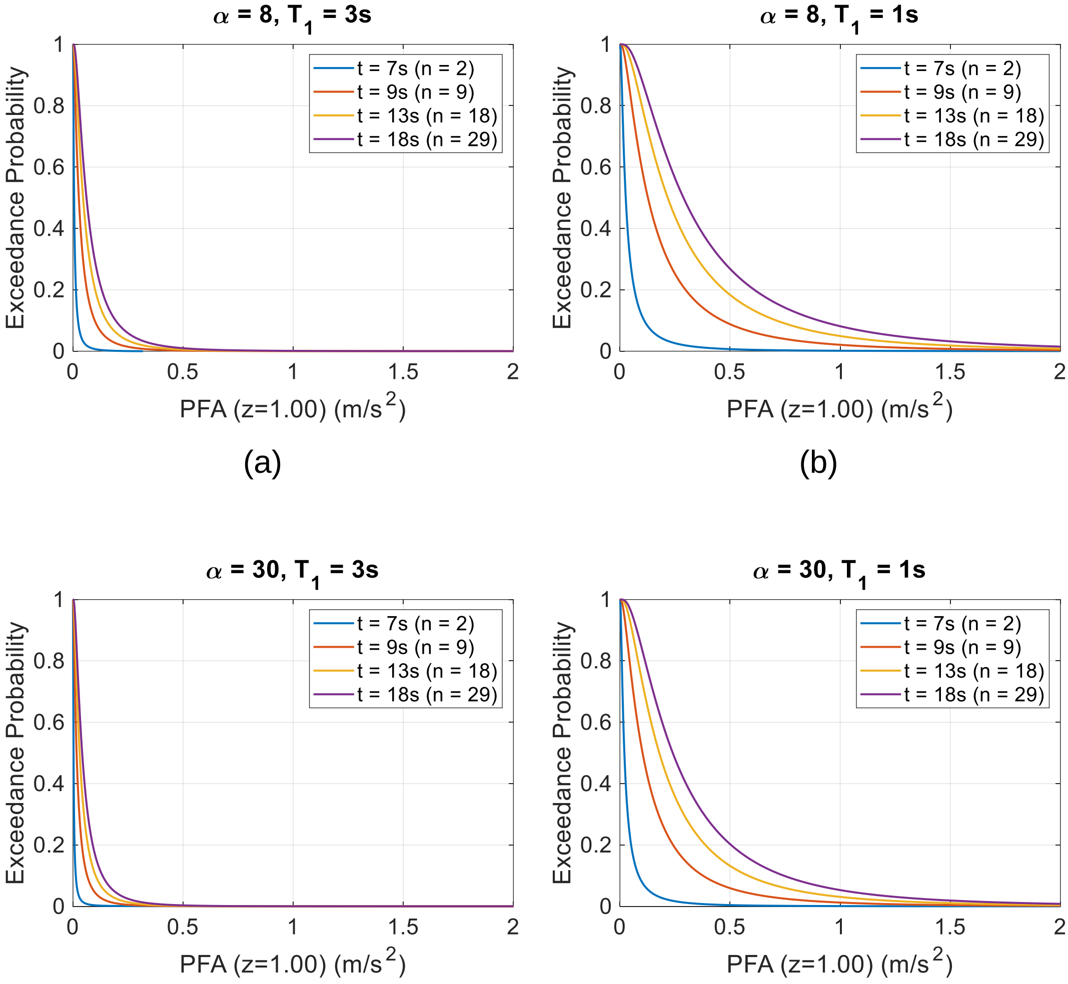
The prediction is carried out on the basis of the information gathered from 18 seismic stations (i.e. 13s after the earthquake's origin), as it is sufficiently close to the one relative to the instant of time in which all the stations have estimated with reliable accuracy the location of earthquake and the magnitude of the event and , as Iervolino et al. (2009) observed for PGA.

To explore the application of the prediction equations derived previously, exceedance probability curves for MIDR and PFA have been computed (Figure 32 and Figure 33). The simulation was performed by adopting two values of $\alpha$ , 8 and 30, for both the sites of Naples and S. Angelo dei Lombardi, and by selecting fundamental periods equal to 3 s in Naples (considering, for instance, the high-rise buildings located in the newly developed business area of the city; Figure 34) and 1s in S. Angelo dei Lombardi (considering mid-rise RC buildings).



(a) (b) (c) (d)

*Figure 32. Simulation of a M6 EQ and results at the sites of Naples (left) and S. Angelo dei Lombardi (right): (a), (b) predicted exceedance probability of MIDR( $\alpha$ =8) at the two locations (T1=3s for Naples, T1=1s for S. Angelo dei L.); (c), (d) predicted exceedance probability of MIDR ( $\alpha$ =30).*



(a) (b)

(c) (d)

*Figure 33. Simulation of a M6 EQ and results at the sites of Naples (left) and S. Angelo dei Lombardi (right): (a), (b) predicted exceedance probability of PFA($\alpha$ =8, z=1.00) at the two locations (T1=3s for Naples, T1=1s for S. Angelo dei L.); (c), (d) predicted exceedance probability of PFA ($\alpha$ =30, z=1.00).*

*Figure 34. Newly developed business district of Naples.*

As expected, the building response in terms of MIDR and PFA predicted at the location of S. Angelo dei Lombardi is higher than that characterising Naples, for the particular event simulated, as demonstrated by the curves plotted in Figure 32 and Figure 33.

Also, it can be observed that the exceedance probabilities of the building response parameters are subjected to only very small variations when different values of lateral stiffness ratio are considered. The latter is consistent with Miranda (1999), who pointed out that variations of $\alpha$ mainly affect the location along the height of the structure at which maximum interstorey drift ratios and peak floor accelerations are attained, rather than the maximum values they actually reach, which are quite stable.

The second part of the simulation consists in the generation of real-time seismic hazard and building response maps of the Campania region in terms of PGA, MIDR and PFA, computed by adopting the new predictive model developed. Similarly, the $M_w$ 6 earthquake scenario previously introduced is considered.

The maps illustrated in Figure 35, Figure 36, and Figure 37, show the median values of PGA, MIDR and PFA, for particular values of $T_1$ and $\alpha$ , and refer to the real-time seismic hazard in terms of ground acceleration and building response, computed after 13s from the earthquake's origin. This time window was chosen to be in line with Iervolino et al. (2009), who found that after 13s from the origin of the seismic event (i.e. 18 stations triggered out of 29), the prediction of the seismic hazard at a site is sufficiently stable and further information from the remaining stations does not provide significant improvements to the real-time estimate.

The maps illustrated in Figure 35, Figure 36, and Figure 37 can then be adopted for the activation of real-time mitigation actions, that can be related to the demands in buildings in terms of IDR or PFA. Some examples of these actions might include: 1) stopping elevators at the nearest floor if a pre-defined critical PFA value is exceeded, to allow occupants to evacuate; or 2) real-time assessments of the floor-shaking sensed by occupant, to explore their levels of comfort before the arrival of the earthquake.

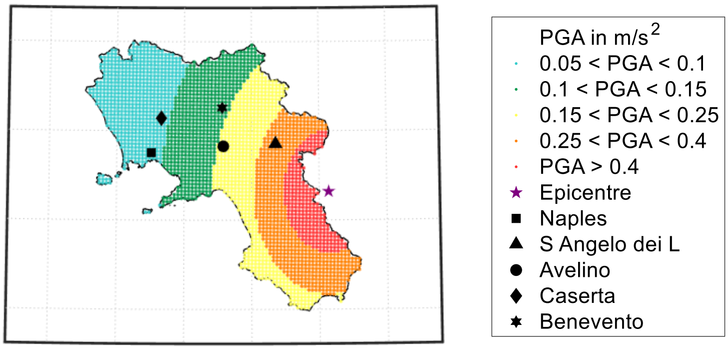


*Figure 35. Hazard map for the Campania region showing median values of PGA for a M6 seismic event.*

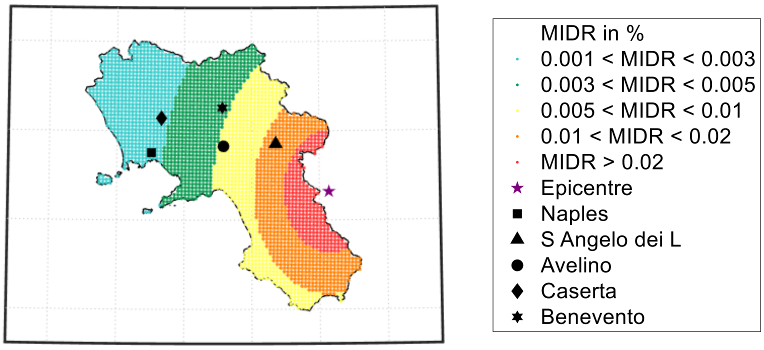


*Figure 36. EDP map in terms of median values of MIDR for a M6 event. T1=1s,* $\alpha$ *=8.*

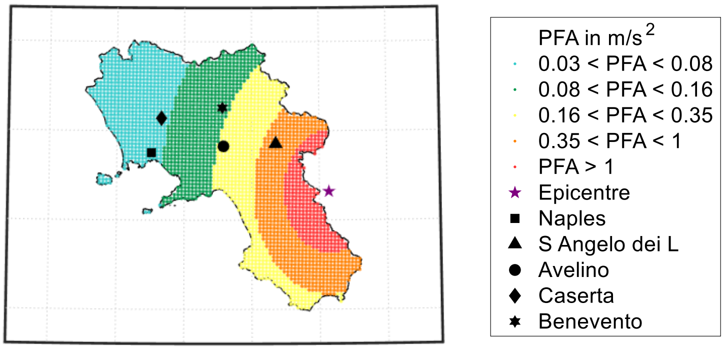


*Figure 37. EDP map in terms of median values PFA for a M6 event. T1=0.3s, z=1.00,* $\alpha$ *=8.*

## 5.6 Conclusions

The chapter presented herein represents the first approach for real-time building response assessment based on the information provided by EEW, rather than current practice based on Intensity Measures (i.e., Peak Ground Acceleration).

A simplified continuous model, consisting of a combination of a flexural beam and a shear beam, was adopted for the computation of EDPs (IDR and PFA), for a broad variety of building typologies. By just modifying two parameters (the lateral stiffness ratio, $\alpha$, and the natural period of oscillation of the building, $T_1$), different lateral load resisting systems (from shear wall systems to moment resisting frames systems) and different height of buildings (from low-rise buildings to high-rise buildings) could be simulated. 45 different structures were modelled, considering three values of $\alpha$ and 15 natural periods of oscillation.

Numerical simulations were performed for the 45 structures, subjecting them to a set of 589 ground motions recorded in the Italian region. The criteria for the selection of the events was as follow: a) minimum magnitude of the event equal to 5 $M_w$, and b) epicentral distances shorter than 200km. At this point, the powerful advantages of the continuous model adopted were visible. A total of 53,010 analyses were carried out in a considerable short period of time. It is important to highlight that fast analyses were necessary as a large database was essential for the calibration of the new Building Response Prediction Equations.

The results from the simulations, in terms of MIDR, IDR and PFA, were collected and organised, so multilinear regressions could be performed for each EDP. A functional form proposed for the Italian region was considered in this study. The coefficients given by the regression were statistically analysed (standard deviations, residuals and p-values), showing reliable results.

The new building response prediction equations have proved to reliably correlate and fit the seismic demand in terms of MIDR, IDR and PFA, with the earthquake source parameters (epicentral distance and magnitude of the earthquake).

The new predictive models have shown their efficiency on a real-time EEW example applied in the Campania Region. Two outcomes were obtained from this application: 1) Real-time Exceedance probability curves in terms of Engineering Demands Parameters and 2) Real-time Building Response maps.

Considering Performance-Based Earthquake Engineering, future works and development of the approach presented herein might include a further extension of equation (17), to predict the expected loss in a structure conditional on the measures given by the seismic sensors (Iervolino, 2011). This information can then contain information on the interest of stakeholders and insurance agencies, for decision making about alarm issuances. This can be achieved by including two more integrals into Eq. (17), conditioning Damage Measures (DM) on EDP $\left(dm \mid edp\right)$, and conditioning the losses (L) on DM $\left(l \mid dm\right)$, for instance. The new equation can then be implemented in a structure specific EEW design procedure to calibrate alarm thresholds, that are optimal for the reduction of losses, including scenarios of the costs related to false and missed alarms.

# Chapter 6. A Likert Scale-Based Model for Benchmarking Operational Capacity, Organizational Resilience, and Disaster Risk Reduction

As explained in Chapter 1.2 of this thesis, this reports is intended as a cross-disciplinary study of EEW, combining technical (e.g, engineering and seismology) and social perspectives of EEW. Chapter 4 and 5 focused on the EEW technical components, while Chapter 6 and 7 approach EEW from a socio-organisational point of view.

Chapter 6 introduces a novel Likert-scale that was required for the implementation of the methodological approach presented in Chapter 7. It is a simple and replicable scale that responds to the needs of practicioners and academics for adapting qustionnaires to local contexts, which might be helpful for benchmarking gaps analyses and resilience assessments, as well as operational research. This scale was developed with the aim of being implemented in surveying materials related to EEW and organisational resilience in Mexico City, as explained in Chapter 7.

## 6.1 Introduction

Organizations and societies are increasingly challenged by complex and systemic disaster risk, in which leaders must undertake strategic decisions in conditions of high uncertainty. In order to increase the flexibility of response and preparedness to concurrent, interacting, interconnected, and cascading events, cultural adjustments are required in both research and practice (Pescaroli and Alexander, 2018). Authors such as Linkov et al. (2013) and Helbing (2013) have highlighted the need for new approaches that could help the assessment process to evolve, in order to be more suitable for applications in multiple domains and disciplines. Since then, the state-of-the-art has evolved significantly in terms of both theory and applications. A critical step was the increased prominence given to the understanding of risk and complexity as described in the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015). This international agreement promoted further developments at the interface between academia, research, and practice. For example, UNDRR released a series of practical guides to support the implementation of consistent measurements and datasets, including, for example, the “Words into Action” guidelines on National Risk Assessment (UNISDR, 2017), and the Resilience Scorecard for Cities (UNISDR, 2017). Similarly, new standards on continuity management and organizational resilience, such as the ones by the British Standards Institution, International Organization for Standardization, and National Fire Protection Association included new elements such as those that assess interdependencies and cascading effects (BSI 65000:2014; NFPA1600:1900; ISO 22316:2017; ISO 22301:2019). This has improved the principles used in benchmarking.

This is a fast-evolving field because tools such as resilience-measurement scales are the most basic source of interaction between academia, practitioners, and policymakers (Cutter and Derakhshan, 2019). The academic literature proposes a range of methodologies that are available for measuring disaster risk, resilience, vulnerability, or climate change impact practices, including choices of variables and measurements, depending on the field of reference (Beccari, 2016; Birkmann et al., 2014; Frazier et al., 2013; Gentile et al., 2019; Kelman et al., 2016; Linkov et al., 2013; Twigg, 2015). However, the need for better standardization of indicators and reporting scales faces limitations, in particular in terms of what should be measured, how often, and by whom (Cutter and Derakhshan, 2019). For example, stakeholders working on interconnected risks have suggested the need for cross-disciplinary improvements in defining operational and decision-making thresholds (Pescaroli, 2018). The billion gigabits available online via channels such as social media have raised further challenges to the achievement of reliable quality standards (Alexander, 2015; Kostkova et al., 2003). Moreover, end-user oriented early warning systems, multi-criteria decision support systems, and the scenario-building methods are some of the applied research fields in which updated benchmarking can make a difference and can help manage complexity (Cremen and Galasso, 2020; Pescaroli and Alexander, 2018).

Despite the progress that has been made, the current body of literature seems to lack a simple-to-use model that could provide benchmarking between different forms of assessment. In other words, the state-of-the-art is extensive, but it is missing a simple alternative framework of reference for cross-disciplinary assessments in those contexts in which existing scales and standards may be unsuitable, challenging, or impossible to be applied. This chapter started with explicitly stating the real-world need that emerged in research on integrating organizational resilience and earthquake early warnings in Latin America. Further evidence and justification of need came from the experience of collaborating with stakeholders in Europe and Japan on operational resilience to cascading and interconnected risk. The following sections briefly review the methodological background and propose a rationale for a new Likert scale based on a response model for the assessment of operational gaps, organizational resilience, and disaster reduction capacity, as reported in Chapter 6.3. The principal goal of this chapter is to propose a simple-to-use, replicable, and adaptable tool that could be used as a benchmark across studies for anchoring information and assessing it in the field of data collection against benchmarks in a context distinguished by low levels of knowledge, training, or awareness.

## 6.2 General Considerations in Rating Scales, Anchoring, and Benchmarking

Research and practice need reliable data. The literature has extensively discussed the role of quantitative and qualitative methodologies for collecting and analysing evidence, with particular attention to the replicability of the data collection process (Bryman, 2016). Similarly, planning and designing a study is an essential aspect of the development of mixed-method approaches (Creswell, 2014). The common ground across the disciplines is the need to anchor questionnaires and surveys to realistic points of reference in relation to the context in which the data are collected (see, for example, Ahmed et al.

2016; Alexander 2015; Gentile et al. 2019; Hernández-Moreno and Alcántara-Ayala 2017; Pescaroli 2018; Yore and Walker 2019). In the field of business continuity, a questionnaire is often the most important tool for gathering information in order to conduct a business impact analysis and assess the level of organizational resilience (BSI 2014; ISO 2019). Similarly, questionnaires are used to identify possible “performance gaps” or “capacity gaps” that could be reflected in the existence of perceived inadequate or undesirable organizational or operational states (Channon and Sammut-Bonnici, 2014; UNISDR, 2017)

There are two common steps to consider in this process, independent of the field or discipline. First, the questions have to be carefully thought through to assure their consistency and clarity, and to be safeguarded, as much as possible, against bias (Bryman, 2016; Creswell, 2014). Secondly, each answer has to be anchored to a rating scale, which can be defined as “a closed-end question whose answer alternatives are graduated or organized to measure a continuous construct, such as an attitude, opinion, intention, perception, or preference” (Peterson, 2013). At this point, scholars, researchers, and practitioners have to consider a scale of reference, which may be straightforwardly to use a Likert scale (Bryman, 2016; Croasmun and Ostrom, 2011). The next step would involve looking at benchmarking examples such as those given by Brown (2010) and Vagias (2006). Something similar may happen in fieldwork, for example, when it is necessary to assess emergency response capacity, develop a business impact analysis, or benchmark organizational resilience at large (Alexander, 2000, 2015; BSI 2014; ISO 2017).

However, in some cases, contextual limitations would suggest the need to shift the analysis to an approach that differs from the most commonly used scales. Indeed, in some fieldwork, Likert scales from 1 to 5 or 1 to 7 are simply not fit for the local cultural or social environment, or they cannot be reported in labels that use ordinary language or common idioms. Similarly, it is important to consider the qualitative and explanatory nature of the options available in the questionnaires that have to be considered complementary to the numerical values provided in the scales: different interpretation of the numbers can generate some confusion among respondents if not supported by a qualitative rationale, as for example was identified by the National electronic Library for Health project assessing the “quality” of evidence base (Kostkova et al., 2003; Wiseman et al., 2008). For instance, the process of collecting data about capacity, impacts, or preparedness in operational contexts (such as local councils) may be hindered by lack of resources, or failure to embed the process. Thus, anything more complex than what is strictly necessary might not be welcome. In such cases, the solution could be to implement scales from 1 to 3, or use binary answers such as “yes or no.” However, this approach risks oversimplification, which might compromise the outcome of the project (Bryman, 2016; Croasmun and Ostrom, 2011). In addition, experience in the field and dialogue with stakeholders suggest the need to move to a “hybrid” approach that prioritizes clarity, replicability, and consistency across different sectors. The point of the next section is to introduce a 0–3 scale, which could be more easily accessible to respondents, while it reduces the possibility of bias in responses and assures consistency across different measurements and research domains of disaster risk reduction, operational capacities measurement, and organizational resilience.

## 6.3 A New Scale-Based Assessment Model

A novel Likert scale-based assessment model for measuring organizational resilience and gaps in operational and disaster risk reduction capacities is reported in Table 21. It is organized according to the following structure:

**Value.** The numerical value chosen is from 0 to 3, with the additional inclusion of the category “don’t know” as a possible option. The value of the primary assessment criteria is reported in both the disaster resilience scorecard (UNISDR, 2017), and some examples of Likert scales offered by Brown (2010) and Vagias (2006). While developing this value scale, it was recognized that answers may be affected by high uncertainty and low knowledge, and responders may have the tendency to choose the middle value in the ranking. As suggested in the review by Croasmun and Ostrom (2011), the risk of a biased response could be mediated by providing a neutral response option, allowing respondents not to take an opinion if they do not have one. This risk was mediated in the scale proposed herein by including the category “don’t know” as an additional choice. Finally, the numerical value is supported by a visual association with the standard “traffic light colour scheme” that is also used in the dissemination of warnings in order to harmonize the meaning of the numbers for people in different backgrounds and disciplines (Kostkova et al., 2003; Wiseman et al., 2008).

**Category labels.** This section provides some generic examples of descriptive attributes that could be used to develop qualitative answers and ratings that are complementary to the numerical values of the scale. This has been intended as a partial and synthetic list that is derived from the descriptive categories reported by Brown (2010), Vagias (2006), and from a review carried out of the attributes in the categories used by UNISDR (2017) and BSI (2014). In other words, the proposed scale provides enough evidence to be taken as a reference, independent of the question that has been formulated. It does not pretend to be comprehensive.

**Gap outcome.** The gap outcome in Table 21 is intended as a support for the consistency of the outcomes and results of gap analyses, that are defined in this chapter as the processes of assessing and comparing one organization’s objectives and their expected outcomes to understand possible differences in the performance that has been delivered (Channon and Sammut-Bonnici, 2014). This is presented in terms of “inadequate/adequate” or “undesirable/desirable” operational or organizational states (Watkins et al., 2012). First, the states are identified according to the numerical values obtained on the scale. Second, they are anchored to qualitative examples of the Likert scale such as those given by Brown (2010) and Vagias (2006). They can also be anchored to percentages reported in the resilience scorecards by UNISDR (2017). In this case, the numerical thresholds must be considered as generic reference points, and they need to be grounded in a specific context, which may either confirm or challenge their validity.

**Capacity levels.** This label provides a qualitative description of the capacity levels that have been derived from the maturity model integration of Chrissis et al. (2003). This is integrated into the disaster resilience scorecards approach UNISDR (2017). Capacity is intended as “the combination of all the strengths, attributes and resources available within an organization, community or society, to manage and reduce disaster risks and strengthen resilience” (UNDRR terminology, updated 2017).[17]

**Resilience levels.** The resilience levels have been simplified and adapted from the corresponding maturity levels reported in BS65000:2014 (BSI 2014), shifting from a 0–5 scale to a simplified 0–3 scale. In the present work, the term “resilience” is defined as “the ability of an organization to absorb and adapt in changing environment to enable it to deliver its objectives and to survive and prosper” (ISO 2017, p. 4).

*Table 21. A Likert scale-based response model for benchmarking gaps in operational capacity, organizational resilience, and disaster risk reduction capacity*

| **Value** | **0** | **1** | **2** | **3** | **Don’t know** |
|---|---|---|---|---|---|
| **Category labels** | No; little/no; few/no; not at all; never; inadequate; very little. | Basic; limited; lacking; seldom; occasional; partial; occasionally; under-resourced; not actively promoting or pursuing improvements. | Limited or sparsely present; in progress; applied/developed/ validated with some inconsistencies; but not updated; actively promoting or pursuing improvements. | Mostly or completely present; comprehensive; complete; fully integrated; full compliance; full validation; applied consistently across; well established; applied and regularly updated; well established across sectors; constantly improving; higher proportion. | Don’t know |

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[17] https://www.preventionweb.net/terminology/view/7831

| | | | | | |
|---|---|---|---|---|---|
| **Gap outcome** | Undesirable or critical state. Significant and diffused gaps; application in less than 20% of cases. | Moderately undesirable state. Existence of some gaps. Applied and present in more than 20–25% of cases. | Somewhat desirable state. Few gaps, subject to improvements. Applied between 50 and 75%of cases. | Desirable state. No substantial gaps have been perceived. Applied in up to 100% of cases. | |
| **Capacity levels** | Non-existent or to a large extent incomplete capacity, processes are not performed or only partially so. | Limited initial capacity, processes performed, some metrics have been developed but are still fragmented. | Some defined capacity is available. Processes are identified and tailored to the organization, metrics are collected and applied. Some inconsistencies may still be present. | Comprehensive capacity. Processes are well developed and consistently measured or assessed. Baselines are established and measured, problems are identified and fixed. | |
| **Resilience levels** | No measures have been implemented in the organization, lack of coherence, no innovation or flexibility.<br>(BS65000:2014: Immature) | Some measures have been implemented but most of the practices remains informal with limited coordination and fragmented actions.<br>(BS65000:2014: Basic and Managed) | Strategic directions have been set, with understandings of the internal and external context, including its dynamics. Programs and practices are not fully coherent and consistent, but there are steps in place for improving.<br>(BS65000:2014: Established) | Strategies have been developed consistently, and good practices have been applied across departments. Activities have been measured and assessed regularly. A process of continual improvement has been established and is ongoing. The organization demonstrated innovation and flexibility.<br>(BS65000:2014: Predictable, Optimizing) | |

## 6.4 Conclusions

The scale introduced herein provides a replicable, direct model for benchmarking answers, built on the real needs of stakeholders and the feedback obtained from the field. However, like other tools and methodologies that represent the current state of the art, it has some characteristics and limitations that need to be taken into account if it is to be applied effectively. It should be noted that the scale has been developed to provide a flexible assessment for contexts in which there are constraints that prevent one from conducting a wider and more complex analysis. In other words, the rationale of the approach is to maximize the reliability of answers by sacrificing, to some extent, the level of detail when anything more sophisticated is not achievable. This implies that the achievable level of accuracy of the results is lower. In this, there are two complementary considerations. In the first place, ideally, the scale should be used as a basis for developing a more complex form of analysis. In the practice of assessing resilience, this may be derived from guidelines such as those mentioned previously (BSI 2014; European Centre for Disease Prevention and Control 2017; UNISDR 2017). In multidisciplinary research, optimal results may require broader scales, such as one in the range 1 to 7 or 1 to 10 (Croasmun and Ostrom, 2011). Second, a possible alternative to compensate for the reduction in accuracy of the scale when compared to alternatives may be to plan carefully the integration of questionnaires with semi structured interviews or focus groups. This could profitably follow guidelines for mixed-method research such as those provided by Bryman (2016).

In conclusion, this approach does not pretend to be exhaustive, but it provides a practical and flexible reference method for benchmarking that can be adapted to the context in which it is used. For example, in some cases, category labels may require both language translation and changes to reflect sensitivity to cultural variations in the use of terminology. Instead of a limitation, these elements could be seen as an additional strength that could be used to promote testing and further evolution of the model, according to new experiences derived from research and practice. The result could be extended to different disciplines.

# Chapter 7. Integrating earthquake early warnings into business continuity and organisational resilience: lessons learned from Mexico City.

## 7.1 Introduction

In the first half of 2020, we have seen new complex scenarios developing across the globe. Earthquakes, as well as other natural-hazard events, occurred concurrently to the ongoing COVID-19 global pandemic, challenging emergency response in countries such as the United States, Mexico, Croatia or China. However, this is not new and requires a broader vision of the implementation of new disaster risk reduction strategies and the optimisation of such mitigation measures. In 2015, the member states of the United Nations endorsed the *Sendai Framework for Disaster Risk Reduction 2015-2030* (UNISDR, 2015). This document aims to "prevent new and reduce existing disaster risk", highlighting that early warning systems should become a priority and evolve substantially by 2030 (UNISDR, 2015). According to the United Nation's terminology, early warning systems can be intended as "An integrated system of hazard monitoring, forecasting, disaster risk assessment, communication and preparedness activities processes that enable individuals, communities, governments, businesses and others, to take timely action to reduce disaster risks in advance of hazardous events" (UNISDR, Terminology updated February 2017)[18]. New early warning methodologies for complex events should integrate an improved understanding and modelling of hazards, "end-to-end" and "people-centred" decision-support systems/tools, and risk-informed practices and policies needed for the delivery of warnings, and the promotion of common and consistent training for end-users (Pescaroli et al., 2018).

Some research fields related to early warning are more mature than others, as widely discussed in the previous chapters. For example, physical-science and

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[18] https://www.preventionweb.net

engineering modelling and social sciences have already been integrated to model early warning and evacuation in coastal areas, supported by climate change adaptation efforts (Hissel et al., 2014). Regarding EEW systems, much less interdisciplinary works have been developed to date. The technical components of EEW, particularly seismological ones, have been widely reviewed and debated by authors such as Allen and Melgar (2019) and Cremen and Galasso (2020). Yet, there is an urgent need to integrate new technology, engineering modelling, risk drivers, and practices of dissemination of warnings (Herovic et al., 2019; Velazquez et al., 2020). It can be noted that some scholarly literature on EEW has progressed in recent years, investigating people's needs and perceptions towards EEW, and contributed to the understanding of EEW using a community perspective (e.g., Nakayachi et al., 2019; Santos-Reyes, 2019). However, the interaction between organisational needs, priorities, management, and practices, remains mostly fragmented (Velazquez et al., 2020). For example, Blyth (2009) discussed the role of warnings for business continuity and specifically focused on measures for earthquakes; however, the study has only marginally explored how EEW could be used for orienting organisational processes and practices. Studies such as the one by Whitman et al. (2014) analysed organisational resilience (OR) within the context of specific events, but omitted EEW as it is not currently a system available in New Zealand. However, this is not just an issue associated with the limited diffusion of EEW systems. In Japan, Maruya (2013) analysed lessons learned from the Great East Japan Earthquake (2011) for improving business continuity without mentioning specifically the possible use of EEW, while other studies investigated just sectorial applications, such as in hospitals (Horiuchi, 2009). In California, other studies such as the one by Goltz (2002) or Johnson et al. (2016) focused on possible anticipated benefits for organisations, by extending the list of mitigation actions that can be triggered given the warnings provided by the EEW system of California, rather than investigating business continutiy or resilience. This is confirmed by the general gaps in the thematic literature, not tending to bridge the two topics. Authors such as Burnard and Bhamra (2019) highlighted that Operational Resilience could be seen as a dynamic capability composed of both active (adjustment of a system to create a change) and passive (actionless ability to absorb disturbances) forms of resilience, and further research should address how the different components of OR are integrated together. This implies to identify/analyse the gaps, such as operationalising the concept of OR, and the integration of research insights among disciplines, including the analysis of engineering sciences and socio-political systems (Linnenluecke, 2017). In other words, OR could be analysed and applied within different frameworks (e.g., social and technical) that could make the difference for future applications (Pescaroli and Alexander, 2018).

This chapter aims at investigating, by adopting a cross-disciplinary approach, the possible gaps and operational criticalities limiting the integration of the technical components of EEW into practices of OR. In particular, this chapter intends to explore what the public and the private sector need information and training on in order to respond and adapt more effectively to the dissemination of EEW, improving when possible OR.

In this chapter,  OR is defined as "*the ability of an organization to anticipate, prepare for, and respond and adapt to incremental change and sudden disruptions"*(BS 65000:2014). It is intended as a holistic process that includes elements such as adaptive capacity, leadership and culture, having different levels of maturity depending on the implementation status of the measures adopted (BS 65000:2014). One of the essential operational steps for building and improving OR is developing practices of business continuity, intended as the *"capability of an organization to continue the delivery of products and services within acceptable time frames at predefined capacity during a disruption"* (ISO 22301:2019).  This rely on the implementation of a response structure that enables adequate warning and communications, by providing effective business continuity plans that can be defined as the *"documented information that guides an organization to respond to a disruption and resume, recover and restore the delivery of products and services consistent with its business continuity objectives"* (ISO 22301:2019).

In the next sections, an empirical analysis of the case study of Mexico City (Mexico) is proposed. Here, EEW has been developed by the authorities (local and national), but the need for increasing the effectiveness of the system is widely recognised (Santos-Reyes, 2019; Suarez et al., 2009). A mixed-method approach is developed to derive qualitative and quantitative evidence, bridging the social-science and technical (e.g., seismological, engineering) fields. The discussion reflects the lessons learned for improving practices of OR, emergency preparedness and business continuity, and are contextualised in the state-of-the-art on disaster risk reduction and OR, but also following ISO standards[19]. The conclusions suggest possible implications for mitigating complex scenarios and the next steps for future research.

## 7.2 Case study: Mexico City

Mexico City is the capital of Mexico and one of the main economic hubs of Latin America. It has approximately nine million inhabitants, 21 million[20] considering its metropolitan area, which are exposed to socio-economic vulnerabilities, such as population growth and urban development, as well as to natural hazards, such as earthquakes, floods and heatwaves. In particular, its recent history has been distinguished by some major earthquakes causing vast human and economic losses, including the M8.1 Michoacán earthquake of 1985, that led to the early development of the Mexican EEW system (Cuéllar et al., 2017; Espinosa-Aranda et al., 2009, 2011), and the M7.1 Puebla-Morelos earthquake of 2017.

Since 1985, the Mexican EEW system has evolved significatively, achieving three important milestones: a) in 2005, the governments of Mexico City and Oaxaca created the Seismic Alert System of Mexico (SASMEX), that has the capacity to provide warnings between 60 and 120 seconds to Mexico City (Cuéllar et al., 2018); b) in 2010, the government of Mexico City funded a

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[19] https://www.iso.org/home.html

[20] https://www.gob.mx/conapo/documentos/delimitacion-de-las-zonas-metropolitanas-de-mexico-2015

further extension and update of the system, that counts now with 97 stations within SASMEX. Here the warning is publicly disseminated across the city both using fixed speakers and traditional media such as national television and radio broadcasters (Espinosa-Aranda et al., 2009; Santos-Reyes, 2019; Suarez et al., 2009); c) in 2019, the warning thresholds have been updated to include different scenarios that could trigger an alarm, including a magnitude threshold ranging from 5 to 6 depending on the proximity of the target city to the epicentre (Velazquez et al., 2020). In the sole Mexico City, more than 12,000 warning speakers and repeating devices have been installed since 2015 to improve the dissemination of alerts to different organisations and the general public (Santos-Reyes, 2019). The current legislation requires that critical infrastructure, such as hospitals, schools and government buildings, must install EEW devices to receive alerts, integrate them in the emergency and mitigation procedures, and carry out regular drills and exercises (Suárez et al., 2018).

However, there are still various shortfalls associated with the organisational and societal implementation of EEW in the city. First, the public service remains fragmented as not all the urban areas of Mexico City are sufficiently covered with sirens and speakers that disseminate the warning (Velazquez et al., 2020). In addition, private services are available using special receivers that require a paid subscription, but the number of registered users is low (Velazquez et al., 2020). The existence of additional EEW mobile applications represent both an opportunity and a shortfall: although they increase the accessibility of the service, they also can somehow jeopardise the functionality of the official EEW, and therefore create conflicting sources of forecast/information (Reddy, 2019). Similarly, it has been argued the existence of common gaps in education, training, and governance. Although the system is reliable (rarely providing false alarms), the seismic network around Mexico City could be denser with practical implications in terms of variability of predictions (Tajima and Hayashida, 2018), reducing the number of possible missed alarms. At the time of the M7.1 event of the 19th September 2017, a common belief among the citizens of Mexico City was that - in all cases - they would have had 60 seconds between the warning and the arrival of the ground shaking (Santos-Reyes, 2019). When the EEW system instead provided no warning, this created confusion and affected trust. Santos-Reyes (2019) argued the critical need for further development of governance, in particular in terms of training and procedures to follow before, during and after an earthquake (Santos-Reyes, 2019; Suarez et al., 2009).

## 7.3 Methodological approach

This chapter adopted a replicable mixed-method approach (Creswell, 2014), using together semi-structured interviews and questionnaires. The target group was focused on representatives of organisations from the local public and private sectors (including experts from academia) in Mexico City, recruited through a convenience sample and with voluntary participation. The data collection assured the anonymity of participants, assuring that no personal data about individuals was stored/captured. Specifically, a sequential data collection was developed by using first qualitative and then quantitative methods, for the purpose of response to the research questions and hypothesis testing (Palinkas et al., 2011). This process aimed at maximising the complementarity between the interviews and questionnaires, using qualitative data to provide open-ended/in-depth understandings, and quantitative data to provide a significant statistical analysis (Palinkas et al. 2010; Creswell 2014). The main hypothesis aimed at testing one of the research gaps highlighted by Velazquez et al. (2020); if organisations are aware of the EEW system but they have a limited integration in OR, then it was expected that the answers would indicate:

- High levels of perceived utility of the technical tools (providing EEW), but lack of integration in organisational needs and gaps in practices of business continuity;
- Gaps in the definition of some critical information (e.g., the contents of the warning messages) or dissemination practices (e.g., who should have access to more complex warning messages, including lead times, for example);

- Existing issues in terms of jurisdiction, coordination, and accountability;
- The fact that the dissemination of warnings requires additional training and educational measures to integrate EEW into OR.

The empirical literature was reviewed for deriving questions for the data collection and analysis, using as initial references those reported in Velazquez et al. (2020). The development of the contents included in the questionnaire integrated further considerations on the indicators considered in the United Nations Office for disaster risk reduction scorecards (UNISDR, 2017), British Standards on OR (BS 65000:2014) and the *International Standards on Business Continuity* (ISO22301:2019).

A first draft of the semi-structured interviews and online questionnaires was initially derived in English, then translated into Spanish, and codified in this language before the discussion. A careful process of reviewing and piloting was conducted to assure the accessibility of the questions, to corroborate the rationale and fluidity along the questionnaire, and to guarantee that the language and format were contextualised in a local perspective. This was done involving some Mexican staff and students working or studying in the field of disaster risk reduction based at University College London. The results included 15 semi-structured interviews and 78 valid questionnaires that were analysed in sequence and then connected in the discussion (Creswell 2014; Palinkas et al. 2010). The next sections describe in detail the criteria used for developing the data collection and analysis.

### 7.3.1 Semi-structured interviews

The interviews explored the information and training gaps perceived by the organisations in the public and private sector, in order to respond and adapt better to the dissemination of an EEW. The interviews were also targeted considering different expertise and using the author's professional network to contact respondents in the following fields: Local Government, Civil Protection, Private Sector, Academia, disaster risk reduction governmental agencies, NGOs and Civil Societies. The methodological process followed the one described by Harrell and Bradley (2009), defining a replicable protocol for data collection and analysis. The format was such that each interview was expected to last approximately one hour, including four main sections: 1) “*how do public and private organisations use Earthquake Early Warnings?”*, including pros and cons of the system and improvements needed; 2) “*what information and training are available to integrate EEW in organisational procedures?”*; 3) “*has the link between business continuity management, organisational resilience and EEW been established and developed*?”; 4) other priorities and needs, such as personal comments from the interviewees. Each question integrated approximately four-to-five sub-questions that worked as facilitators for the interviewer. The fieldwork took place in January 2020, 13 of 15 interviews were interrogated in-situ, then two were followed up via videoconference. The anonymity of each interviewee was assured by following a two steps process: a first anonymization happened at the time of recording, and no specific reference to the names, organisation, or date of interview were associated with the files. Then, the interviews were transcribed allocating random numeric codes from 0 to 30 during the analysis, which were then reassigned during the answers’ analysis process (Saunders et al., 2015). A content analysis was developed without the support of software following the methodology by Weber (1990). The process aimed at exploring the existence and frequency of concepts associated with four categories of themes described in the study by Velazquez et al. (2020):

- *Operational Sphere*, including tactical elements and tools that influence how EEW is developed and disseminated, such as information on lead times and expected impacts, and the use of tools such as sirens.
- *Political and Governance Sphere*, including aspects associated with the legal framework in which EEW systems are implemented.
- *Social and Behavioural Sphere,* associated with aspects such as local culture, local knowledge and experience with the considered hazard, trust in institutions, and community-based resilience.
- *Organisational Sphere* associated with procedures and practices that integrate EEW actions into business continuity plans and practices.

These must be intended as indicative categories, that are constantly overlapping and interacting each other.

The preliminary outcome was further divided into two sub-themes for comparisons, namely "strengths and opportunities" and "weaknesses and open issues". Deductive analysis was used to confirm or refute the previous hypotheses and results. In contrast, inductive analysis was carried out to obtain more unknown relationships or issues that emerged from the data gathered in each interview. For the inductive analysis, an unbiased coding and indexing process was carried out following the process described by Weber (1990) in order to identify and classify keywords, phrases and sentences that would determine the most common topics raised during each interview.

### 7.3.2 Online questionnaires

Online questionnaires were used complementarily to interviews to support the quantitative assessment of OR maturity and existing gaps in business continuity. The topics investigated were derived from the existing literature such as Alexander (2015); Johnson et al. (2016); Nakayachi et al. (2019); Ohara (2012); Porter( 2016); Santos-Reyes (2019); Suarez et al. (2009). A consistency cross-check was carried out with the critical aspects highlighted in the review Velazquez et al. (2020). This process resulted in 42 questions, divided in four main sections, a) "*Perception of EEW systems";* b) "*Current status of planning for mitigating disruptions"*; c) "*Training needs related to EEW";* d) "*Background"*. The items are reported in their English version in Table 22. The majority of the answers used a Likert scale-based model for benchmarking operational capacity, organizational resilience, and disaster risk reduction developed within the project and explained in Pescaroli et al. (2020). The numerical values of the items varied from 0 to 3, were 0 was associated to an undesirable state, insufficient capacity, and low resilience maturity; and 3 represented a desirable state, comprehensive capacity and higher resilience maturity (Pescaroli et al., 2020). The quantitative values were supported by qualitative descriptive attributes to assure consistency, and the option “don’t know” was available to avoid discretionary answers on intermediate values.

The on-line questionnaire was distributed through the University College London’s Web-Based Survey Tool “Opinio”[21], and was available to be answered between mid-February 2020 and March 2020. The questionnaires were disseminated within the network of the Department of Geography at the Universidad Nacional Autónoma de México (UNAM), and it was supported by ARISE MX[22] (Alianza del Sector Privado para Sociedades Resilientes ante Desastres en México). The latter is a national network of the private sector aimed to support disaster resilience within the aegis of the United Nations’ Office for Disaster risk reduction.

Approximately 100 questionnaires were collected. A threshold of 50% or more answers was used to consider them valid for analysis, reducing the dataset to 78 questionnaires. This was considered a significant result, as the total organisations affiliated to ARISE are approximately 200 in the whole country. The analysis of the answers of each questionnaire was carried out by performing a non-parametric correlation Spearman’s Rho test, using SPSS V.19 (IBM Corp. Released 2019) and Matlab®. This type of analysis was chosen as the input variables obtained from the questionnaire’s answers are of type categorical (discontinuous) and therefore not normally distributed, preventing the adoption of traditional correlation methodologies (e.g., Pearson correlation).

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[21] https://www.ucl.ac.uk/isd/services/learning-teaching/e-learning-services-for-staff/e-learning-core-tools/opinio

[22] https://arise.mx/

*Table 22. Questions (Q) included in the survey*

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| Section 1. Perception of EEW Systems |
| Q 1. How relevant is EEW for your organisation? |
| Q 2. Do you consider EEW as a useful service when considering its current state of development? |
| Q 3. To what extent do you know what to do in case of an EEW? |
| Q 4. Do you think EEW could be useful to limit the disruption of critical services such as communication and transportation? |
| Q 5. Do you think the current development of EEW takes in adequate consideration how they can be integrated in organisational needs? (E.g. operational functions, day to day activities) |
| Q 6. To what extent do you think that local policies are adequate to support the integration of EEW in your organisation’s practices and procedures? |
| Section 2. Current status of planning for mitigating disruptions |
| Q 7. Does your organisation have developed specific plans or procedures to undertake in case of an EEW? (e.g., stop a production process, empty the cash register, close the gas mains) |
| Q 8. Has the business continuity plan of your organisation been updated in the last 18 months? |
| Q 9. To what extent your organisation identified which critical functions/activities could be protected using EEW? |
| Q 10. To what extent your organisation prioritised which critical functions/activities could be protected using EEW? |
| Q 11. To what extent your organisation identified internal responsibilities/liabilities for activating procedures and actions associated with an EEW? |
| Q 12. Is your organisation aware of the official institutions that provide EEW in Mexico City? |
| Q 13. To what extent your organisation identified possible vulnerable categories that could be better protected by activating specific procedures following an EEW? |
| Q 14. Do you consider useful to know the available warning time, before the arrival of the ground shaking at your location? (Specially to activate organisational procedures). |
| Q 15. Considering the Mexican EEW system has included the available lead time in the warning message, has your organisation identified the mitigation actions likely to be activated for short warnings (e.g., 10 seconds), or large warnings (e.g., 60 seconds)? |
| Q 16. Do you consider the Mexican EEW system can initiate beta testing in which warnings include the available warning time? The beta testing would only include those organisations with appropriate structures and capacity to deal with such warnings. |
| Q 17. Do you consider that false alerts can trigger interruption of business continuity, and therefore create economic losses, within your organisation? |

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| Q 18. How often your organisation practice drills for both short and long warnings? |
| How helpful do you think the following tools could be to improve the use of EEW for your organization? |
| Q 19. a) Guidance about good practices and procedures to follow for integrating EEW in your organisation |
| Q 20. b) Legislations that clarify responsibilities associated with actions to undertake when an EEW is released |
| Q 21. c) Guidance on what to do according to the possible time intervals between an EEW and the arrival of the ground shaking at your location (e.g., distinguishing between short warning, long warning and common actions) |
| Q 22. d) Assistance in defining the best continuity strategies for your organisation in case of an EEW |
| Q 23. Please rate the tools enlisted in Qs 19-22, from less useful to more useful, according to their relevance in your organisation. |
| Q 24. Is there anything else that has not been mentioned above that you may find useful? |
| Section 3. Training needs related to EEW |
| Q 25. Have you received enough training to understand the applications of EEW for limiting the disruptions/ helping the continuity of your organisation? |
| Q 26. Did your training (if any) include the implications of EEW for preparedness, response, and recovery? |
| How useful do you think the following training might be? |
| Q 27. Courses to understand how to integrate the EEW into the daily activities of your organisation |
| Q 28. A free short course on how to respond to an EEW in organisation provided by the local authorities |
| Q 29. Roundtable events or tabletop exercises held in the local authorities/community or business organisations |
| Q 30. Freely available guidelines |
| Q 31. On-line free lessons |
| Q 32. Webinars and on-line videos with basic instructions to undertake in the case of an EEW |
| Q 33. Please rate the training enlisted in Qs 27-32, from less useful to more useful, according to their relevance in your organisation. |
| Q 34. Is there anything else that has not been mentioned that you may find useful to support training on EEW? |
| Section 4. Background |
| Q 35. Does your organisation have access/is registered to EEW? |
| Q 36. Have you ever participated in training sessions or workshops on how to use efficiently an EEW in your organisation? |

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| Q 37. Are you aware of how long the warning time in case of EEW is? |
| Q 38. What is your opinion about false alerts? |
| Q 39. What is your level of education? |
| Q 40. What is your affiliation? |
| Q 41. What is your gender? |
| Q 42. Do you have any other comments? |

## 7.4 Interview results

This section introduces the findings of the interviews regarding the operational, political and governance, social and behavioural, and organisational spheres described in the methodology of this chapter. As a general comment, it is possible to note a general agreement among the respondents on the strength of the technological component of the EEW system in contrast with the weakness of some political, social, and organizational aspects.

### 7.4.1 Operational Sphere

All the interviews (15/15) pointed out that the Mexican EEW system had good technical reliability. For example, the respondent (R) 02 highlighted that *“technically, the system works well, and few false alerts have been released since it was launched (1986)”.* All respondents agreed on the fact that the system is technically reliable, with no significant issues observed. The problems are mostly associated with the implementation and translation of an EEW into action. As a substantial downfall within the operational sphere, all the respondents noted a lack of full geographic coverage, which was associated with limited resources available. R30 suggested very clearly that “*the potential for the (Mexican) EEW system to grow and have larger coverage is huge, but everything relies on the funding from the local, regional and federal government”*. An element directly connected to this was that lack of speakers deployed across the city, which implied gaps in the public dissemination of the alerts. According to the direct experience of R21, *“during the January 2020 drill, we did not even hear the simulated EEW”*.

Similarly, R03 highlighted that *“many places in Mexico City, where shaking has been quite intense during past events, do not have any speaker. People* *located in these areas do not have access to the alerts".* Similarly, all the respondents were concerned about the low number of users that, in accordance to the Mexican law, must receive the warnings, raising the point that the operational and governance/political spheres are strictly interlinked. As R05 highlighted *"it is unbelievable that not all the schools, hospitals and offices in the city have access to the warning, why not?".* According to Suárez et al. (2018), all strategic buildings like hospitals, security buildings and offices, are legally required to contain devices for receiving EEW alerts in Mexico City.

It was highlighted the need of supporting the understanding of organisations about the realistic possibility of having "false alerts", that instead are still not perceived as a possible outcome of the EEW and were orienting the trust in the technical system. R04 pointed out "*the Mexican EEW system (in Mexico City) is not helpful for organisations because it is not even effective for individuals. If you carry out a study on individuals, you will realise that people do not believe in the system. Even drills are now considered just a nice time to catch up and chat with colleagues, people do not believe in them anymore*". This was complementary to the issue perceived by the majority of the respondents about the lack of a clear strategy to disseminate operational procedures to end users, thus reducing the capacity of the EEW and its corresponding warnings to influence individual behaviours. All the respondents agreed also that there was a lot of potential for operational improvements, in particular by including the available warning time between the release of the alert and the arrival of the shaking at a given location. This was considered an essential piece of information to be included among all the interviews but needed to be supported by the complementary development of training strategies.

### 7.4.2 Political and Governance Sphere

All the respondents agreed about the existence of significant opportunities for implementing new policies and legislation on EEW in Mexico, with potential for fostering collaborations between academia and practices. In particular, R07 and R11 argued that research institutes and universities are quite open to collaborations with the government, especially when it comes to disaster risk reduction. However, there was concern among all the respondents that nobody was taking the lead in activating the implementation of such collaboration process.

A common element of criticality was the lack of interaction between governmental bodies and academic institutions. All respondents agreed that during previous governments (prior to 2018), the local Civil Protection Department and similar bodies ignored the advice given by research institutes with expertise in disaster risk reduction. According to some respondents, and in particular R11 and R21, it was possible to note some more collaborations between some academic institutions and the local Civil Protection developed since the elections of 2018 and the change of government. However, the respondents from academia generally pointed out the need for higher involvement of research institutions for achieving optimal results in disaster risk reduction. Academics also pointed out that the capacity of the Civil Protection may have been undermined by a lack of adequate funding. As pointed out by R04 "*in a country where security is an everyday concern at any governmental scale, focusing funds for disaster risk reduction might not be the priority"*. Similarly, it was pointed out that the fragmentation of rules, scopes, and goals towards disaster risk reductions and mitigation actions, between the local, regional, and national administration could affect the local Civil Protection.

It was also highlighted by all the respondents the lack of a consistent governance approach and specific policies to develop an EWW culture that could support the population and organisations, communication and knowledge transfer of lessons learned after an event, and assuring the inclusion of vulnerable categories. R03 and R05 pointed out in particular the potential to inform people about the nature of earthquakes and their impacts, the EEW system, and disaster risk reduction strategies, which are topics that have always been received minor attention by the government. For example, the 2017 earthquake created a window of opportunity to develop some knowledge transfer with the public that was highly receptive, but *“2 years have passed…and this was a very badly missed chance”* (R03). In December 2019, three earthquake national drills or exercises were integrated into policies for gathering data and improving evacuation protocols. However, most of the respondents suggested concerns about the actual outcomes due to an approach that limited the achievement of collecting useful feedback, mainly due to inefficient organisation and coordination efforts when the drills were performed. For example, R12 highlighted that *“we have expressed many times that there is a lack of feedback among the drills; we are told there will be feedback, but this never happened. This is not a good practice as every single drill is the same as previous ones, and people get bored, not taking seriously future drills”.*

Finally, for all the participants, it was clear that the warning providers (SASMEX) are not in charge of the public and organisational training. However, it was highlighted the lack of consistent governance on accountability, particularly through two aspects that need to be addressed:

1) the “liability” of releasing the warnings. In the interviews, R30 highlighted as a critical point that: “*this is a system that is likely to fail, this is normal, and everyone needs to understand it. There are many uncertainties involved in the EEW process, and triggering false alerts might be not avoided. However, when false alerts lead to losses, there should be a political body paying for them. This covers individual aspects (like a heart attack) or economics losses due to interruption of business continuity (for organisations)”.*
2) Resolving the conflict between public and private EEW systems. All respondents agreed that only the official EEW system should provide alerts and releasing alerts without the consent of those in charge of the system should be penalised. R04 in particular, stated that *“the number of alerts (false) triggered by private systems sometimes is even dangerous. Once I was walking in the corridor of my institution and many people were concerned as their private app alerted them about*

*an incoming earthquake. There was no warning actually and the official system did not warn anything at all. These private apps just induce panic in the community".* However, private systems were seen very positively by all the respondents as a tool that could add functions to the official system and might be quite helpful for organisations and the public once "synchronised*"* with the official alerts.

### 7.4.3 Social and Behavioural Sphere

The presence of some widespread issues in the political and governance sphere do not seem to compromise the presence of positive aspects from the social and behavioural perspectives. All the respondents pointed out that the population of Mexico City learned from previous experience; *"The population was aware of some of the 'basics' (of EEW) at the individual and collective levels, using surprisingly positively social media for the dissemination of correct information"* R(04). Specifically, R25 indicated that *"the use of social media in the aftermath of the 19 September2017 earthquake allowed the dissemination of true information (and slightly prevented fake news to be spread). The population accessed more non-governmental media efforts that gained a lot of credibility as the content shared helped a lot in the recovery and response phases of the disaster"*. It was also highlighted the potential for developing good practices at the local level, in particular, building on the will to cooperate and receive training demonstrated by the population during past events. However, better strategies for communication and education among residents were needed. According to R06 *"governmental bodies talk about a culture of prevention, that is a concept completely unknown by residents in Mexico City and even by (some of) those bodies that try to teach it".* For all the respondents this was associated in particular with the lack of clear differences corresponding to the behaviours to undertake before, during and after events. "*These actions require a strong and targeted action, and not the release of more complicated communication messages that will not be properly understood by the public as they do not have appropriate training and education strategies*" (R04).

Similarly, actions were needed to tackle the common public idea that false alerts were mostly useful to provide the chances of extra drills without being aware that they could also be the manifestation of some technical problems (and produce losses). Indeed, R11 highlighted that *“if the system is not working, people need to know it is not working. What the public need to accept is that the system can fail”.* A critical issue that could cause problems is related to the fact that people are confused about who officially issues warnings, which is consistent with some of the political and governance issues reported in the previous section. R06 argued that *“earthquakes is a topic being covered by so many institutions and private companies in Mexico that people are confused about who actually triggers the alerts. People are so confused that they do not even know whom to blame in case of a false alert”.* On the positive side, common thinking among the respondents was that all these aspects created the conditions to introduce some standard disaster risk reduction education across the country, starting from a young age (6-12), and including training on individual actions related to the actions to undertake considering different warning times. R25 pointed out that volunteers could represent a vital added value for high-magnitude events as “*the response of the community and organised civil societies was a key factor for the emergent response and recovery after the 2017 earthquakes. The government did not have the capacity to deal with the disaster, it was quite clear*”.

A critical point highlighted by all the respondents was that the population was suffering of widespread lack of trust in political bodies, such as Civil Protection, and sometimes in the EEW system, which may even hamper positive efforts in the implementation of new measures. Unfortunately, this was associated with the common believe that corruption is a key factor that slows down the development of a disaster risk reduction culture in Mexico and more actions are needed to produce a societal change on this regard.

### 7.4.4 Organisational Sphere

All respondents suggested that public and private organisations could be essential actors to improve the entire EEW planning and response process:

they could build on what they have already developed/achieved, such as evacuations plans, to achieve optimal levels of resilience. R15 highlighted that *"organisations can be benefited from the EEW system; however, there has been minimal information on how to implement the alerts. I believe there is a great opportunity to start the integration of organisations and the EEW by registering and training key organisations. Procedures could be tested with the registered users, and then guidelines could be launched to the rest of the organisations that did not register*". Similarly, some respondents were sceptical about the guidelines and training provided by government actors, such as the Civil Protection, in particular for the availability of qualified personnel. R08 commented that she/he *"would never allow Civil Protection 'experts' to come and design any protocols within her/his company. I do not trust their technical expertise*". R09 and R14 raised doubts about the availability of technical and cross-disciplinary expertise within the staff of the organisations involved in preparedness and response (e.g., Civil Protection).

The academic sector had some additional points associated with training and education. First, they noted that the private sector was not well involved in the implementation of protocols for business continuity provided by governmental bodies. Therefore the private sector has to invest in getting their own training and updated protocols (as they have the finance to do it). Second, that the expertise and knowledge about procedures to be activated after the issuance of an EEW is already available in universities, but it has not been used (see points in the previous spheres). In conclusion, it is clear an overall lack of consistency on business continuity planning, which is not included sufficiently in EEW alerts. According to some interviewees, most of the organisations do not know that they can implement actions. For example, R06 brought the example of *"hospitals, where staff are more concerned about evacuating people and themselves, rather than protecting dangerous items/materials".* This was also confirmed by some non -academic respondents. R08 clarified that *"the actions implemented once the warning is released are a consequence of protocols that have been designed without keeping in mind particular EEW aspects. It is just a coincidence".*

Some respondent from the public and private sector had similar concerns, including both specific and general elements. R01 reinforced the message of a current lack of training for organisations about options of response actions, including essential factors such as the impact of protection/repair works (if possible) before evacuation. R01 believed that *“there should be an emergency protocol for the protection of pieces in museums. To be honest, I do not understand why we do not have one*”. The same respondent also manifested concerns about a general lack of specific organisational procedures that targeted vulnerable societal categories.

The actual status of things portraited by R03 was that *“in schools, during the 2017 earthquakes, the teachers were asking the kids to run away from buildings during the earthquake (rather than drop, cover and hold on). Not even the people who are educated know the basic rules to be followed during shaking’.* In conclusion, the lack of clear accountability between the public/private components of EEW reported in the previous spheres had consequences at the operational level. Having different institutions delivering alerts confuse organisations and do not allow the implementations of emergency protocols. R13 suggested tha*t “no single organisation will implement any kind of emergency protocols (following the alert), if they do not know the available time to carry out a particular action. It is extremely dangerous (in terms of economic losses) to carry out emergency actions blindfolded; it does not make any sense”.*

## 7.5 Questionnaire results

This section summarises the findings and results obtained from the 78 questionnaires considered as valid (50% answered at least) in this chapter.

### 7.5.1 Background of the respondents

The respondents formed a mixed background of organisations that had access or were registered to the EEW service (27%). 39% had no access or had not registered yet, and the remaining third of them did not know the answer. In general, the level of training was inadequate among all respondents. A solid majority never participated in training sessions or workshops on how to use efficiently EEW in their organisation (64%), nearly 24% received training but not in the last 18 months, and just 12% were trained and updated in the last 18 months. Most people believed that there was a given constant time between the release of the warning and the arrival of the shaking (overall 69%). In comparison, one third (31%) was aware of the existence of variability (Figure 38).

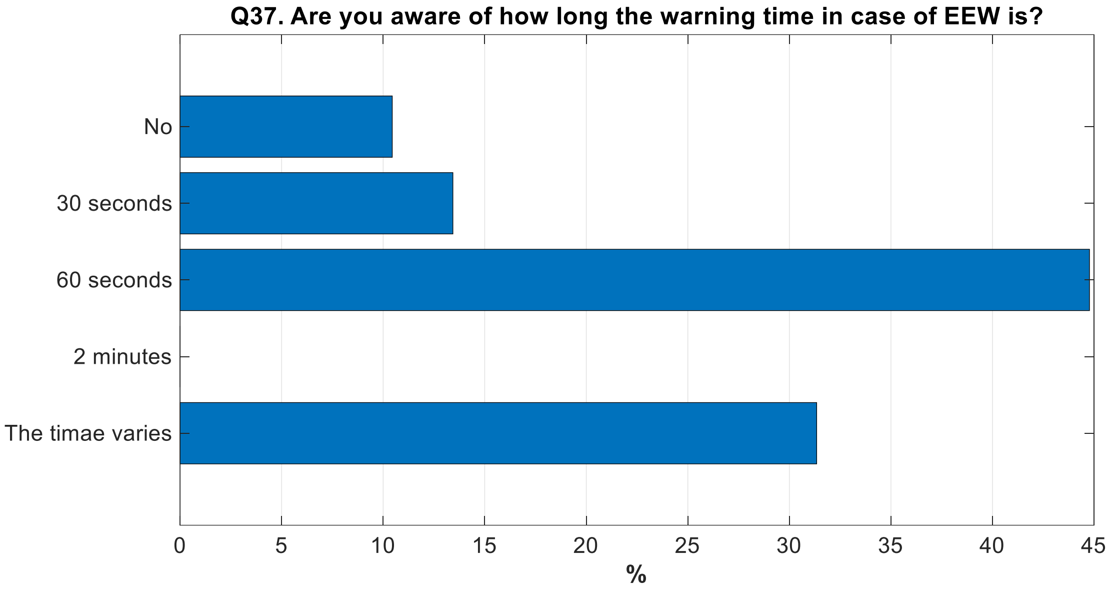

*Figure 38. 'Q37. Are you aware of how long the warning time in case of EEW is?*

The majority of the respondents had a strongly negative perception of false alerts, and they found them unacceptable (61%). Their affiliations included a well-balanced mix of the public and private sector, with some particular spread among education institutions that could be referred to both public and private sectors (Figure 39).

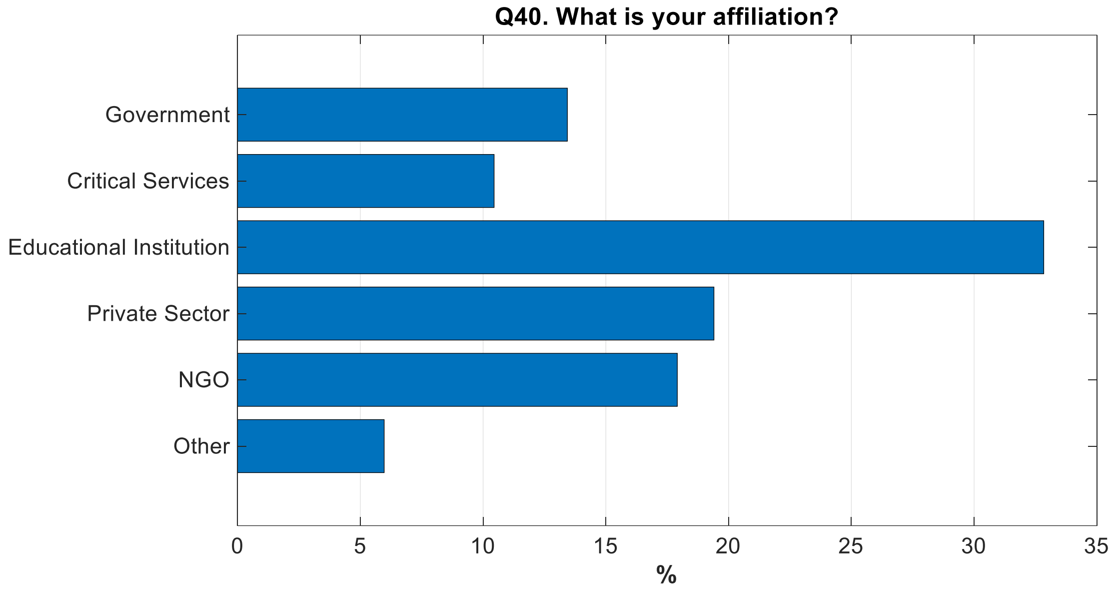

*Figure 39. Q40. What is your affiliation?*

Finally, the respondents had a very good level of education, as 91% of them had some form of academic degrees, and there was a balance among the gender of the respondents, males and female (both 48%), while other 4% defined themselves as “other” or preferred not to answer.

### 7.5.2 Perceptions of the EEW system

Nearly all the respondents agreed that EEW is relevant for their organisations (84%). The majority of the respondents considered it a useful service that needed improvements (63%). At the same time, less than a third recognised it is useful in its actual form (22%), and a minority suggested that its development was insufficient (11%). Just 4% argued that the service was not useful at all. 66% of the respondents knew what to do in the case of an alert, and 30% suggested that they knew it, but they need more information/training.

The vast majority of respondents suggested that the development of the EEW considered the integration with organisational needs, such as operational functions (Figure 40). However, a total of 58% highlighted that there were substantial deficiencies, or these needs were insufficiently addressed.

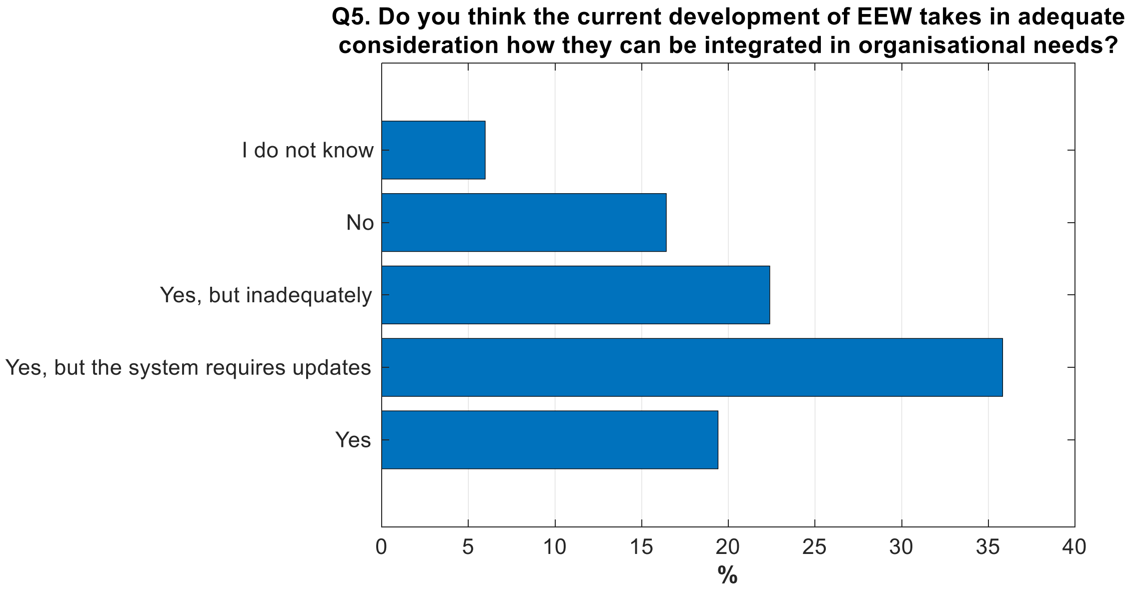

*Figure 40. Q5. Do you think the current development of EEWs takes in adequate consideration how they can be integrated in organisational needs?*

The answers tended to be polarised, even assessing the status of local policies to support the integration of EEW in organisation practices and procedures (Figure 41). What emerges is that the majority of respondents suggested the existence of a supporting local legal framework (14%), that has though deficiencies and gaps in 67% of the cases. However, it can be noted that the negative component associated with a total lack of implementation (17%) was stronger that in Question 5 (Figure 40).

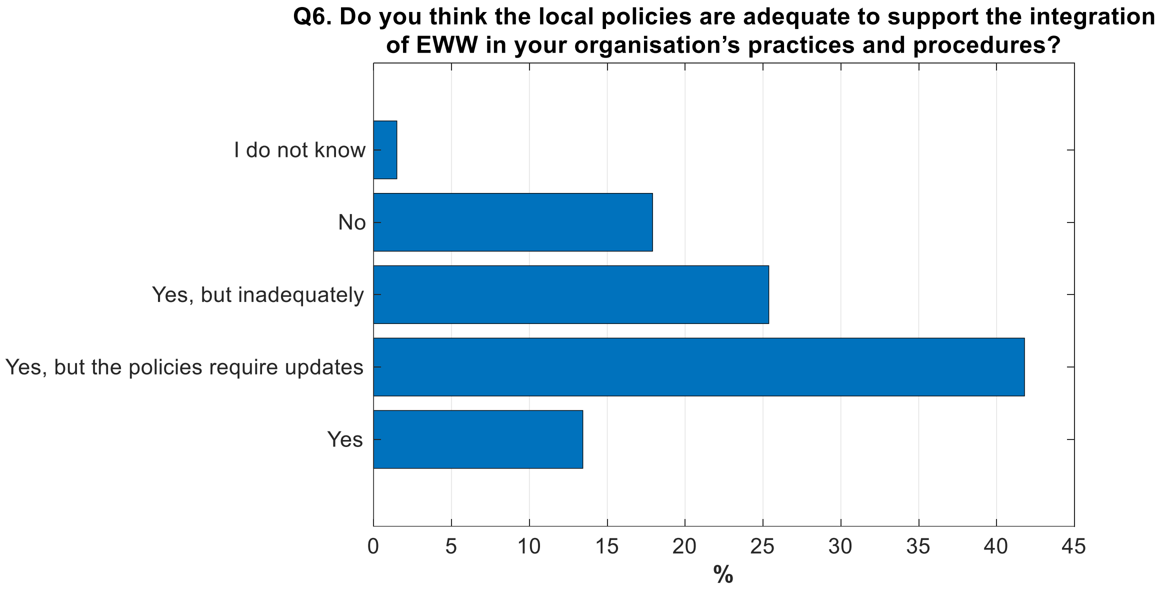

*Figure 41. Q6. Do you think the local policies are adequate to support the integration of EWWs in your organisation's practices and procedures?*

### 7.5.3 Status of planning for mitigating disruptions

The current status of planning was too fragmented. Most of the organisation had some specific plans or procedures to undertake in case of EEW (79%), however, it was possible to observe a distinction between elementary plans (31%) and specific ones (34%), as reported in Figure 42.

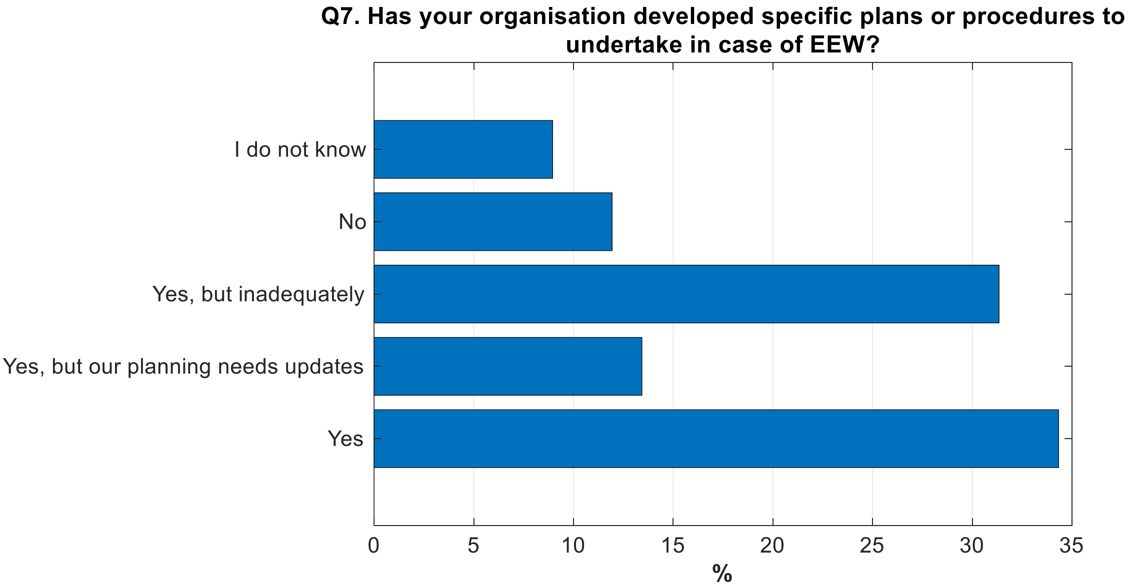

*Figure 42. Q7. Has your organisation developed specific plans or procedures to undertake in case of EEWs?*

Similarly, there was a split between organisations that did not have continuity plans updated (Figure 43) in the last 18 months (37%), organisations that updated them in the last 18 months (36%), and respondents that did not know the answer (27%). The situation in terms of identifying and prioritising critical functions and activities was distinguished again by a fragmentation of answers. Figure 44 shows insufficient levels of identified critical activities (42%), and equivalent levels between fully positive answers (30%), in which a dominant component of responses was in all cases suggesting the need for updates (28%).

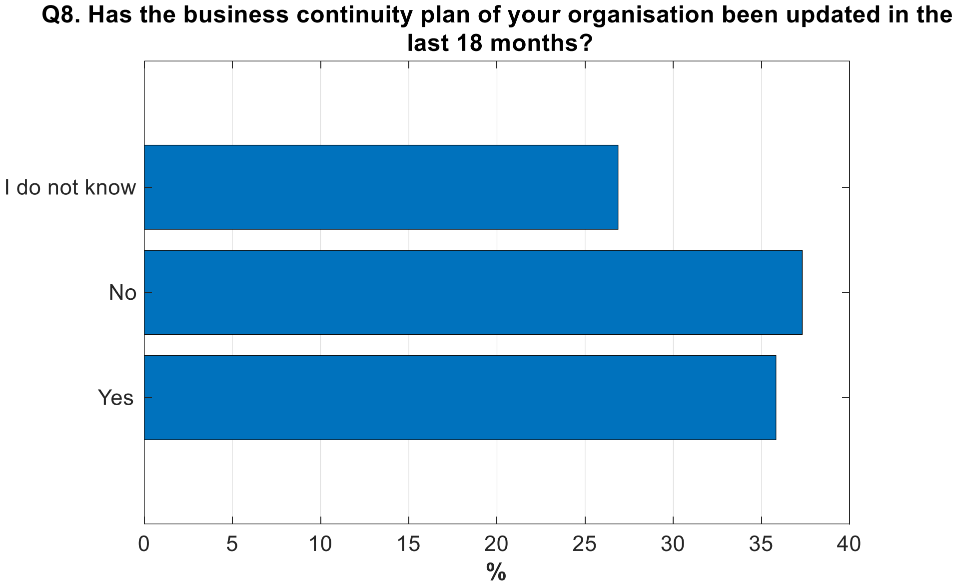

*Figure 43. Q8. Has the business continuity plan of your organisation been updated in the last 18 months?*

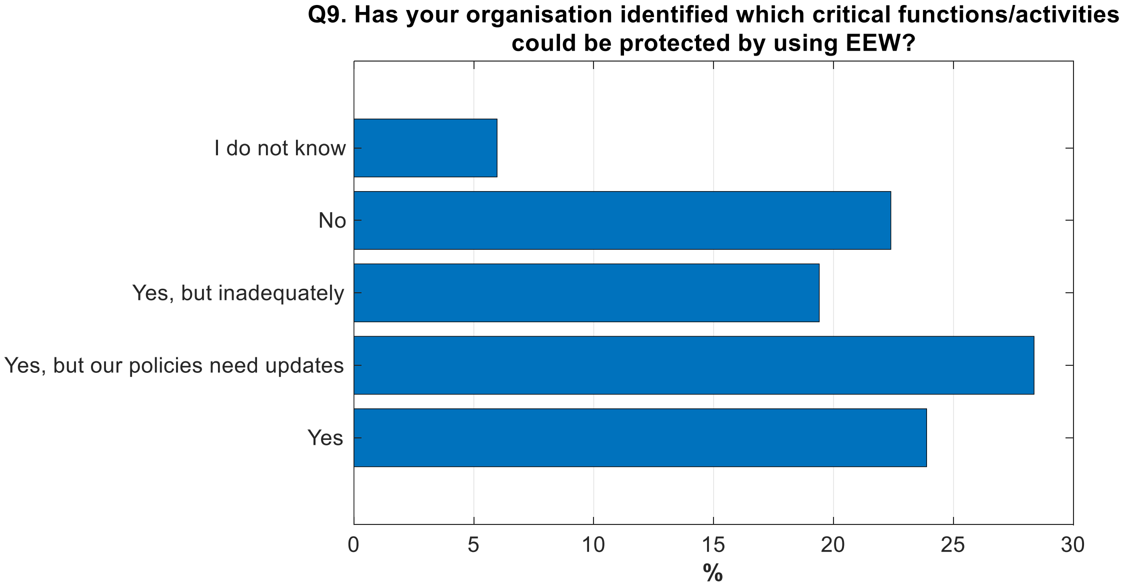

*Figure 44. Q9. Has your organisation identified which critical functions/activities could be protected by using EEWs?*

Instead, organisations had fully prioritised (30%) which critical functions/activities could be protected by using the alerts provided by the EEW, though in some cases updates were required (31%). 15% of the organisations were not able to prioritise the critical functions that can be protected, while 19% recognised they did carry out the prioritisation process but inadequately, as reported in Figure 45.

The situation was better than expected, considering the identification of internal responsibilities/liabilities for activating procedures and actions associated with EEW. The majority of the organisations indicated that they are aware of those individuals responsible (and accountable) of activating mitigation actions following an alert (58%), while 42% could not recognise the people in charge.

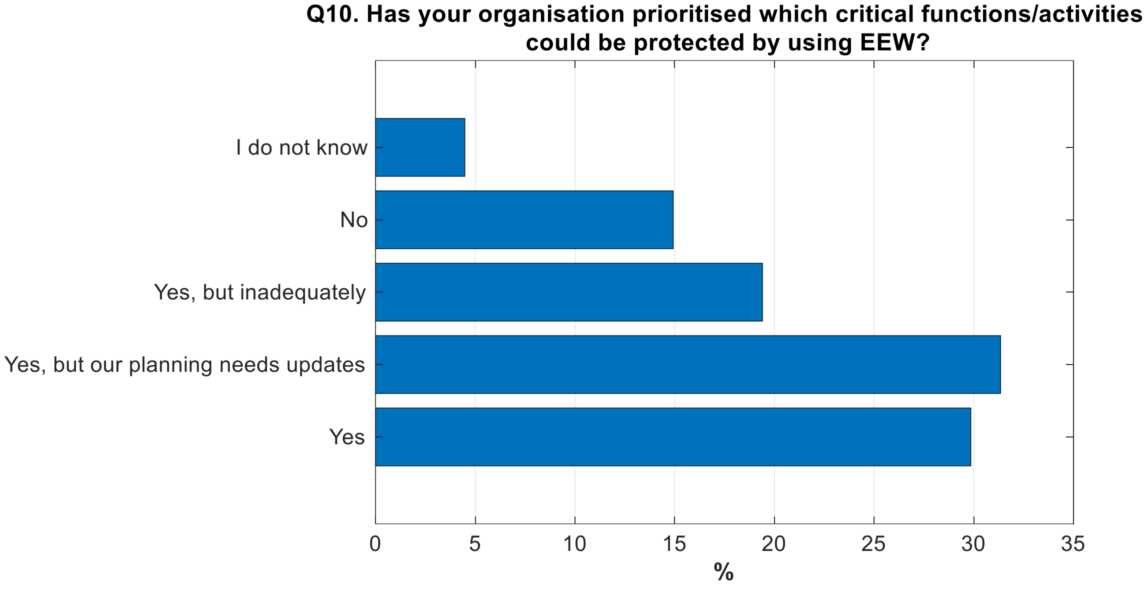

*Figure 45. Q10. Has your organisation prioritised which critical functions/activities could be protected by using EEWs?*

The levels of awareness about which official institutions release EEW in Mexico City were surprisingly fragmented, as 49% of the respondents indicated to be aware, 19% were not aware, and 32% did not know. However, considering that the respondents had the open possibility to write down "who provides the warnings", it was realised that in fact, 45% of those that mentioned being aware were actually wrong. For example, some responses indicate "fire fighters" or "civil protection" as alerts providers, that instead are end users of EEW. These results unequivocally highlight confusion in this regard.

The majority of respondents indicated a lack of a consistent approach for protecting vulnerable categories within their organisations in case of EEW, highlighting a clean split between positive and negative values (Figure 46). Despite, there was a total agreement among the respondents about the perceived utility of knowing the available warning time before the arrival of ground shaking (90%).

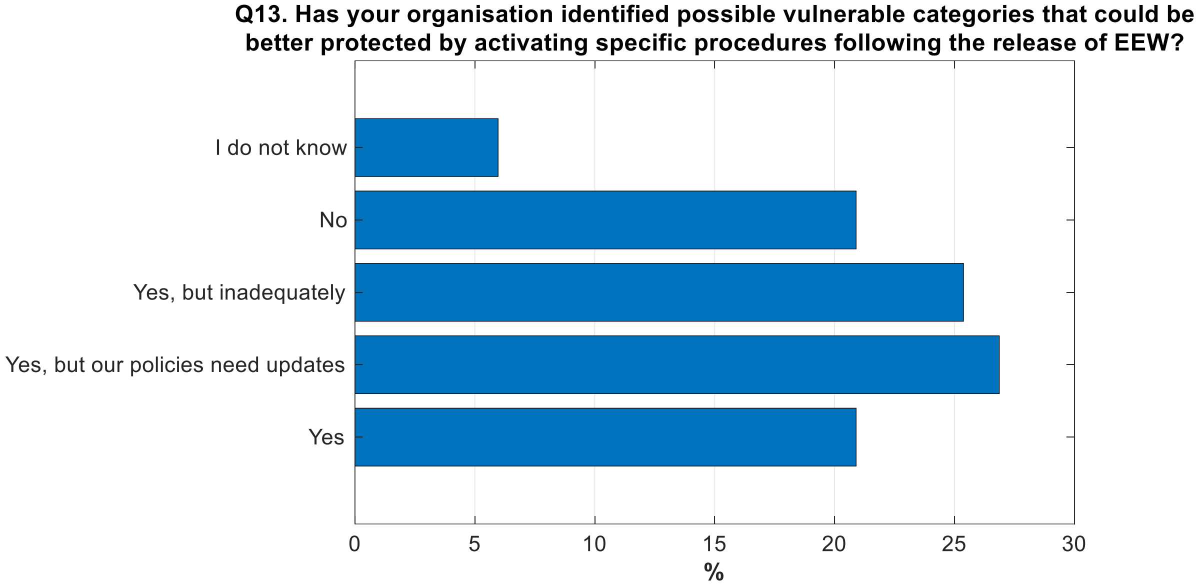

*Figure 46. Q13. Has your organisation identified possible vulnerable categories that could be better protected by activating specific procedures following the release of EEWs?*

The absence of a clear warning time in the alert message likely induced fragmented answers, with a thin majority of organisation not identifying mitigation actions likely to be activated for short warnings or long warnings (27%), insufficiently identifying them (22%), while planning had to be updated in organisations to activate the procedures (24%), and just 15% of organisations did identify the actions consistently; 12% of respondents did not know. Complementary to this point, most of the respondents agreed that it would be useful to run a beta test for organisations where warnings would include the available warning time (87%). There was a clear perception that false alerts could impact business continuity, creating economic losses. However, more uncertainty was associated with the magnitude of the possible impact, which was not known (33%), or needed to be re-evaluated (33%). It was clear just for a minority of responses (10%). EEW drills were practised mostly once in some organisations (40%), or three times a year (40%). A small minority practised more than three times a year (12%), and nearly nobody did do it at all (6%).

### 7.5.4 Training needs related to EEW

All the measures suggested for improving the use of EEW in organisations were mostly perceived as very useful, with similar values associated with guidance about good practices, legislations, guidance on what to do according to possible warning times, and assistance in defining the best continuity strategies. The most useful tool was considered the guidance about good practices and procedures to follow for integrating EEW in the respondents' organisation, followed by guidance on what to do according to the possible time intervals between the signal and the arrival of the shakes (Figure 47) .

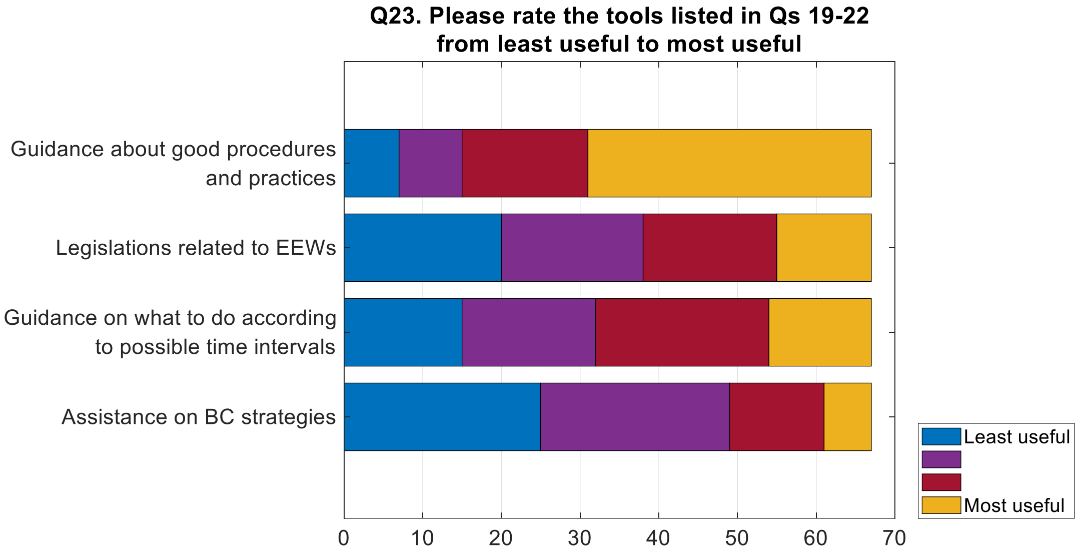

*Figure 47. Q23. Please rate the tools listed in Qs 19-22 from least useful to most useful*

The majority of respondents (64%) did not receive enough training to understand the applications of EEW for limiting the disruption of their organisations. To those who did receive training, their courses did not include the implications of EEW related to preparedness, response, and recovery (37%). All the actions were included in 21% of cases, and 8% in some of the options available. A significant number of respondents chose "I do not know" (34%), that was the suggested option for those who had received no training at all on the subject.

Most of the training options available were judged very positively. When asked to prioritise from the most useful to least useful, the respondents prioritised courses to understand how to integrate the EEW into the daily activities of their organisation, and the availability of free short courses on how to respond to EEWs in organisations, provided by local authorities (Figure 48).

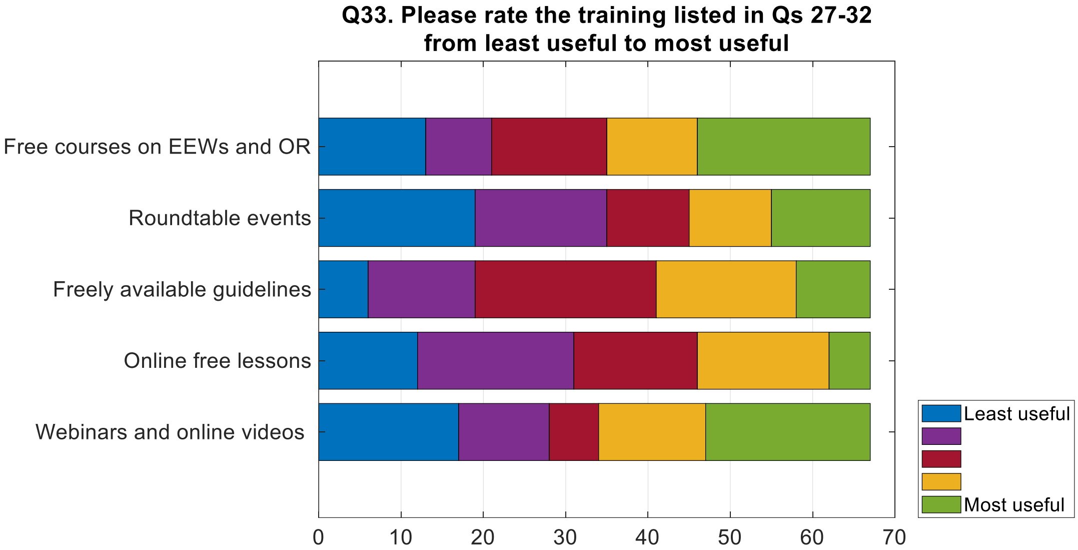

*Figure 48. Q33. Please rate the training listed in Qs 27-32','from least useful to most useful*

This section had some active comments on what the respondents may find more useful, and in particular the following aspects were included: "include social media for training in organisations, involving tv and radio messages". Most of the people indicated the need to ban private systems if not coordinated with the central/official EEW system.

### 7.5.5 Correlations among answers

The analysis highlighted a substantial number of correlations among the answers to the questions reported in Table 22. Particular focus was assigned on those correlations in which p-values where less than 0.01, as this value (or smaller) rejects the null hypothesis that states that the pair of answers being compared are not related (i.e., their empirical correlation coefficient is not significantly different from zero). Then, the correlation coefficients for each pair of answers (with p-value<0.01) were computed, selecting those pairs with correlation coefficients closer to -1 or 1 (values close to -1 indicate negative correlations and values close to 1 indicate positive correlations; coefficients close to 0 express no correlation between the variables tested). For the particular case of the database used for this analysis, all the correlation coefficients resulted positive. Table 23 enlists the stronger correlations (larger than 0.3) found after the analysis, and the description between such correlations is explained below:

- The stronger values were between Q 30 (guidelines), Q 31 (online lessons), Q 32 (webinars). This result indicated that the vast majority of the participants require/want/need the training listed in Q 30, 31 and 32.
- Q 9 (identification of critical functions) was positively correlated with Q 10 (prioritisation of critical functions).
- Q 13. (identify vulnerable categories) was positively correlated with Q 15. (identification of the mitigation for short and long warnings).
- Q 19. (Guidance about good practices) was positively correlated with Q 21 (Guidance on what to do according to the possible time intervals), highlighting organisations that needed guidance, either related to general and specific information.
- Q 25. (received enough training) was positively correlated with Q 26. (implications of EEW).
- Q7 (developed specific plans or procedures) was positively correlated with both Q10 (prioritisation of critical functions) and Q 11 (identification of responsibilities). This confirms and reinforces the rationale already proposed for the relation between Q 9 and Q 10.
- Q 10. (prioritised of critical functions) was positively correlated with Q 17 (impact of false alerts).
- A strong correlation was found between Q 9 (identification of critical functions) and Q17 (false alerts as sources of disruptions).
- The training options had strong values that were correlated among each other’s (Q 27-31).
- The development of specific plans or procedures to undertake in case of EEW **(**Q 7) was strongly correlated with many other variables.

- Q 12 (awareness of the official institutions) was also positively correlated with Q30 (Participation to training session and workshops).
- Finally, there is a strong correlation between Q 11 (identification of internal responsibilities) and Q 16 (beta testing in organisations).

Surprisingly, there was not any correlation between gender and education that often have some influence on levels of risk perceptions. Moreover, no correlations were found between the size of the organisations, while we may have argued that larger organisations had higher maturity levels. Affiliation categories were also not significant, while we were expecting some differences between sectors, but in this case, they may have simply been invisible by the fragmentation of the categories included in the analysis. Further considerations derived by the correlations will support the discussion section of this chapter.

*Table 23. Stronger correlations among the answers of the questionnaire. The correlations were selected only if p-value<0.01, and the correlation coefficient was larger than 0.3.*

| #Q | #Q | p-value | Correlation Coefficient |
|---|---|---|---|
| **30** | 31 | 0.0000 | 0.754 |
| **31** | 32 | 0.0000 | 0.750 |
| **9** | 10 | 0.0000 | 0.692 |
| **13** | 15 | 0.0000 | 0.645 |
| **19** | 21 | 0.0000 | 0.606 |
| **25** | 26 | 0.0000 | 0.594 |
| **7** | 10 | 0.0000 | 0.553 |
| **7** | 11 | 0.0000 | 0.549 |
| **10** | 17 | 0.0000 | 0.494 |
| **9** | 17 | 0.0003 | 0.43 |
| **27** | 31 | 0.0010 | 0.394 |
| **12** | 30 | 0.0017 | 0.376 |
| **11** | 16 | 0.0079 | 0.322 |

## 7.6 Discussion

The analysis of the results validated that organisations are aware of the EEW system. However, they have a limited integration in OR, providing new insights for understanding the existing gaps and needs in EEW practices. In line with what was expected, the analysis showed that organisations in Mexico City were generally aware of the EEW system and considered it a handy tool. However, this was associated with low-to-medium levels of resilience maturity following the benchmarking scale proposed by Pescaroli et al. (2020), and the need of improvements in how warnings are translated in practices of business continuity. The general perceptions of EEW reported in the questionnaires and interviews reflect the idea that this tool, when available, can play an essential role in ensuring effective disaster response. However, higher maturity levels are dependent both on the development of the technical tools (seismological algorithms, decision-support systems, etc.) and its access/coverage to all community and stakeholders' groups, as suggested for example in the case of multi-hazard early warnings in the resilience scorecards for cities (UNISDR, 2017). The analysis also verified that some answers to the questionnaires were entirely wrong. It is argued that specific organisations may have started a process of integration between the operational practices and the EEW, but, due to different causes, such as lack of adequate training, they may have proceeded unintentionally in the wrong direction. This point is supported by the high number of answers in the responses indicating that respondents find all the measures listed in the previous section as possible points for improvements.

The data obtained defines some gaps that can be considered the intersections between the field of disaster risk reduction, emergency planning, business continuity and organisational resilience. Business continuity and emergency management plans are normally perceived as useful by organisations representatives, but need to be frequently practised (e.g., Whitman et al., 2014). The data presented here for Mexico City highlights a tendency of organisations to consider the integration between EEW and their operational functions but suffering some substantial deficiencies and fragmentation in practices associated with their operational context, including some critical gaps in policies and training. This is a common problem across all the organisation fields that participated in the interviews/questionnaires. Despite being a well-established point in the state-of-the-art and in policies, such as the *Sendai Framework for Disaster Reduction*, integrating the technical and organisational components is often neglected in the current practices of EEW across the world (Allen and Melgar, 2019; Velazquez et al., 2020).

The next sections analyse *three overlapping gaps* that emerge when considering the data collected in the perspective of OR and business continuity (Figure 49). Indeed, a wider reflection can be drawn using literature and standards that do not refer specifically to EEW, but includes guidance on the general principles and enabling properties for developing organisational resilience as a holistic process, such as the ones proposed by BS65000:2014, and Burnard and Bhamra (2019) .

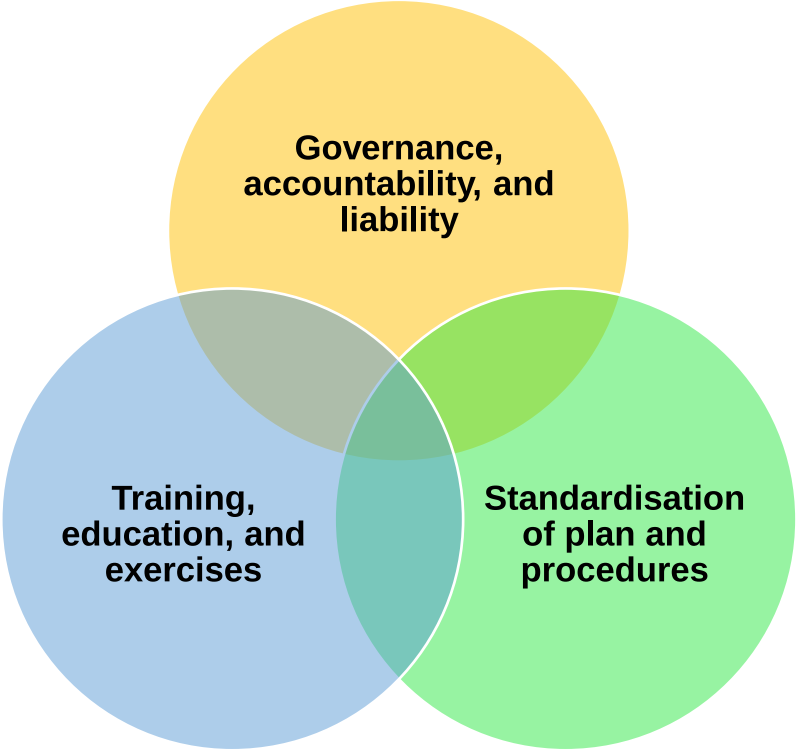

*Figure 49. Critical gaps in how EEW is translated into organisational resilience in Mexico City*

### 7.6.1 Accountability, governance, and jurisdiction

Gaps in Governance, accountability, and jurisdiction include aspects such as coordination between the public and the private actors of EEW. For organisations, this can be associated with the components of situational awareness and the levels of a consistent strategy in terms of governance (BS 65000:2019). However, it refers also to more general components of framing organisations in their operational context, including third parties and stakeholders (ISO 220301:2019). The interviews showed that the public and private EEW systems in Mexico City have complementarities that could be exploited for developing a better and more effective service. However, these are undermined by the lack of a clear accountability and liability strategy related to how the message is issued, disseminated, and how policies are implemented. This gap reveals more directly the structural challenges of disaster risk reduction (Alexander, 2000), and the gaps of the operational capacity of local authorities in Mexico City (Alexander, 2015). However, it can also be associated with system dynamics affecting the resilience of individual organisations (Burnard and Brahma, 2020). Operational activities should be aligned and developed coherently considering aspects such as assets management and risk, and collaboration management, to enable both active and passive resilience (Burnard and Bhamra, 2019).

The data evolve the picture about the need for stronger accountability and liability policies, also provided by studies such as the ones by Suarez et al. (2009) or Alexander (2015). Indeed, there is a need to increase efforts to enhance coordination among actors such as the EEW providers and local authorities (Civil Protection, for example) (Alexander, 2015; Santos-Reyes, 2019). There is a clear issue of coverage and in fact, the questionnaires pointed out that 39% of the respondents were not registered to the EEW service, and another third were not aware of the answer. Similarly, the questionnaires highlight a diffused lack of awareness about which official institutions release an EEW in Mexico City (Q 12), including a surprising 45% of the respondents that thought to know the answer and instead identified the wrong institutions. In other words, as suggested in the interviews, there is a lack of clear accountability between the public/private components of EEW, and this challenges the planning and management assumptions at the operational level. This includes practical questions such as the compensation in case of false alerts, but also implies the need for a clear definition of “who has to do what” (identification of duties), and how risk is owned both at the governmental level, among the management of the private EEW systems, and at the level of organisations. Indeed, the definition of “interested parties” and legal and “regulatory requirements” are among one the first steps needed for understanding the organisation and its context for business continuity purposes (ISO 22301:2019). Effective governance is essential to encourage innovations and investments, while legal and regulatory constraints can act as limits of the desirable outcomes and actions of an organisation (BS 65000:2014). A critical point for all the respondents to the interviews was that the population was suffering of widespread lack of trust in political bodies, including recurrent challenges such as corruption and management. This cannot be considered a surprise. Alexander (2000) defined this as one of the existing negative pieces of evidence that could undermine the effectiveness of disaster risk reduction strategies, including early warnings. Issues associated with inter-agency coordination and the need for a clear strategy for disseminating operational procedures may be rooted in how the system itself has been structured and how the responsibility for managing it has been attributed both within organisations and in the governance domain. The Japanese experience on EEW and organisational resilience has highlighted further the need to enforce the process of accountability as a whole, both in the public and private sector, integrating bottom-up and top-down perspectives (Maruya, 2013; Velazquez et al., 2020). In general, the Japanese experience showed that: “if a local government does not have a business continuity plan, there are concerns that companies acting in the area are not evaluated properly by the government and it would be a restrictive factor in the diffusion of such planning”. Therefore, public and private organizations should advance simultaneously to strengthen their business continuity ability” (Maruya, 2013). A better involvement of scientific and academic actors may represent a further potential for many interviewees, in line with the suggestions of the *Sendai Framework for Disaster risk reduction* (UNISDR, 2015).

### 7.6.2 Standardisation of plans and procedures

The gaps in standardisation of plans and procedures involve considerations on the larger domain of business continuity, and the need of different internal and external communication procedures (ISO 22301:2019). This could be referred in particular to the needs associated with bringing coherence in terms of prioritising and informing operational activities and ensuring business continuity (BS 65000:2014; ISO 22301:21019). The qualitative and quantitative responses derived a fragmented scenario about how EEW is integrated into planning and procedures, with high polarisation between responses. In line with the perceptions of the high utility of EEW, most of the respondents to the questionnaires undertake some sort of protection actions when an EEW alarm is released, but these were inadequate or needed updates. The many correlations between Q 7 and other variables confirmed the understanding of continuity management as a process that needs to be updated and supported by policies. In particular, it was possible to see Q 7 (development of specific plans or procedures ) being related to Q 8 (Business continuity plans-updates), Q 9 (identification of critical functions), Q 10 (prioritisation of critical functions), and Q 13 (identification of vulnerable categories). The answers of Q 9 (identification of critical functions) and Q 10 (prioritisation of critical functions) provide an interesting outcome as more positive values were attributed to the prioritisation of critical functions, that is a step that follows and is dependent on how critical functions are identified. The rationale of those questions was assessing the steps needed for developing a business impact analysis (ISO 22301:2019), which is one of the cornerstones of business continuity. In other words, it is likely that a significant number of organisations developed the process wrongly, or overplayed their own maturity level, as is already visible in the answers collected from the questionnaires. This may create some serious problems in how critical risk is recognised, as well as in the organisations capacity to adapt to evolving conditions (BS65000:2014). The correlations between Q 9 and Q 10 also suggest that there could be a lack of awareness of the issues that could be rooted if wrong training processes are undertaken.

Similarly, the correlations between planning and prioritisation of critical activities (Q 7, Q 11) may be associated with the implementation of the planning process as a whole but this may be simply have been implemented wrongly. The interviews help further to define the picture, suggesting the possibility that the shortfall may be specific to the implementation phase where some generic protocols have been designed without considering the implications of EEW, or the understanding of the specific differences between business continuity and emergency planning. Better use of drills and exercises may also be supporting this process (Blyth, 2009). Indeed, resilience is enhanced and achieved through steps such as developing business continuity and updated business continuity plans. Warnings, including EEW, have to maintain procedures that include communicating both internally and externally, coordinating with stakeholders and other interested parties (ISO 223019:2019). This aspect can also be referred to the challenges of operational emergency planning (Alexander, 2015), and business continuity (Blyth, 2009).

The integration of vulnerable categories remains a neglected topic for the organisations interviewed, though this is generally aligned with how this topic is integrated into emergency planning at large (Alexander, 2015). However, the interesting correlation between Q 13 (identification of vulnerable categories) and Q 15 (identification of the possible mitigation actions for short and long warnings) supports the idea that the identification of vulnerable categories implies a focused action that could be in general associated with higher organisational maturity levels and scenarios. Indeed, the standardisation of practices and procedures is a critical element to address when facing the decisional uncertainties associated with EEW, on which the results both confirm and diverge with the existing state-of-the-art. In parallel, the qualitative and quantitative data suggest that more information about the lead time is urgently needed at least in terms of beta testing. Adding the available time to the warning may orient the capacity to identify more effective mitigation actions, including those for vulnerable categories. This confirms that the perception of organisations on the need for available time is similar to the one of the general public, as pointed by Santos-Reyes (2019) and Velazquez et al. (2020). According to Blyth (2009), the limited time available implies that the “initial response to a warning must therefore be well practised and proven in order to be effective”. However, there are also some differences with the existing state-of-the-art. First, the picture that can be derived by both interviews and questionnaires suggest that the use of lead time may depend on the maturity levels of each organisations. The analysis showed a correlation between the identification of internal responsibilities and the option of beta testing, suggesting that organisations that could be considered more mature could also do a better use of additional information (available lead time). This data would confirm and expand what was already noted by Johnson et al. (2016): implementation actions have to be targeted to different groups, and large companies may have different social and organisational dynamics requiring tailoring solutions. Secondly, the majority of the responses had a strongly negative perception of false alerts. The correlations between the identification of critical function and the perception of false alerts highlights that more mature organisations in the resilience scale see clearly false alerts as sources of disturbance rather than a potential. This result is divergent from the literature that analyses the general population, where it is suggested that the tendency to accept and tolerate false alarms where the system is public is acceptable and even a chance for additional exercises (Allen et al., 2017, 2018; Goltz, 2002; Herovic et al., 2019; Reddy, 2019). This is a very relevant remark, adopting an organisational and economic perspective because it points out the existence of different needs for targeting groups that need to be considered for specific strategies and policies, for example in terms of liability and training. The correlations between Q 10 (prioritisation of critical functions) and Q 17 (impact of false alerts) implies that prioritisation of critical functions leads to better awareness on how organisations may be affected economically by a false alert. However, if this is done completely or partially wrong, also the impact may be misunderstood.

### 7.6.3 Training, education and exercises

Training and education focused on organisation's needs, including expertise from science and the need for developing different services. This could be referred to the need of activating practices for strengthening the organisations (BS65000:2014) and has to be framed in a broader collaborative approach between the public and private sector (Alexander, 2000; 2015; Blyth 2009). There is no doubt that this training, education, and exercising are the pillars of building effective business continuity and organisational resilience (Blyth, 2009), and for developing organisational resilience (Gibson and Tarrant, 2010). Indeed, practical training and education are essential for enabling the flexibility of response (BS 65000:2019). They have to be seen as part of the process that organisations have to undertake for creating competencies that are needed for minimise disruptions (ISO 22301:2019). By adopting a broader perspective on disaster risk reduction, they can act as positive or negative feedback loops (Alexander, 2000).

It is interesting to note that, according to the questionnaires, a strong majority of the respondents knew what to do in case of an alert. However, the semi-structured interviews were less optimistic and suggested to look more carefully to the data. The vast majority of respondents to the questionnaires wrongly believed in a given time between the issuance of the warning and the arrival of the shaking. At the same time, just one third was aware of the existence of variability. Similarly, it was already mentioned in the previous sections the existence of possible misunderstandings and wrong information about how EEW should be integrated in organisational resilience (e.g. Q 9-Q 10, Q 12). Additionally, the substantial majority of respondents did not receive enough training to understand all the applications of EEW for their organisations. Less than one-third of the respondents participated in training sessions on how to use EEW efficiently in their organisations, and these were not happening frequently nor updated. As argued by Johnson et al. (2016), it is essential that the implementation of the EEW system is supported by training strategies and practices that are not self-standing, but must be properly explained and understood, assuring communication and information sharing between the companies and first responders.

The use of drills and exercises evidenced in the questionnaires seems quite frequent, though it could be simply associated to the yearly drill promoted by the national government. The semi-structured answers pointed out that may be a problem of quality more than quantity, as their use becomes routinely or not used adequately to define gaps in practices. However, it is known that a proper use of drills and exercise (both simulations, tabletop, and integrated) could make the difference for testing planning and strategies (Blyth, 2009; Maruya, 2013; Alexander, 2015). The case study may be distinguished then by a wrong perception of reaction capacity, associated with the combination of inadequate protocols, improper use of drills, and training. The statistical correlations show how these could have negatively and positively influenced the overall picture. The awareness of official institutions towards EEW (Q 12), in which a consistent percentage of the answers was wrong, was correlated with participation in training sessions and workshops (Q 30).

Similarly, higher levels of training received was associated with better self-awareness about implications of EEW, as expected, considering that less training also implies fewer explanations about the implications of EEW for the business continuity process. All the responses collected in the study suggest a cross-cutting need for new training with priority for Q 30 (guidelines), Q 31 (online lessons), and Q 32 (webinars), that may highlight the need for independent training with more flexibility for learning, structured to reinforce and consolidate the existing capacity. This is not a surprise, as Alexander (2000) highlighted how training and education are some of the measures that could be used to mediate negative feedback loops in disaster risk reduction.

## 7.7 Conclusions

The analysis and discussion defined that integrating EEW into organisational resilience, business continuity, and disaster risk reduction is not just a technical issue nor cannot be limited to the need for disseminating information.

Instead, it implies taking actions both on internal and external drivers of resilience. The case study suggests taking actions and filling the gaps in three critical domains: 1) Governance, accountability and liability; 2) Standardisation of plans and procedures; 3) Training and education. These can be considered clear overlapping areas between the field of organisational resilience and disaster risk reduction, where possible gaps have to be understood in the socio-political-operational context of reference (Alexander, 2000, 2015; Annarelli and Nonino, 2016; Linnenluecke, 2017; Burnard and Brahma, 2019; Pescaroli and Alexander, 2018)

Although the results must be considered context-depended, the integration of standards on business continuity and organisational resilience give the basis for further generalisations and replicability on other case studies.

This study does not pretend to be exhaustive, but it aims to provide a first step to fill an existing gap of research on EEW. The author also recognises the existence of many limitations, that could be considered the starting point for future cross-disciplinary studies in the sector. First, we recognise that some correlations between the answers in the dataset were limited by the lack of participation of certain infrastructure providers, such as the water provider network, or the limited access of small and informal enterprises outside the ARISE domain. Secondly, it was decided to focus the analysis on the planning components of organisational resilience more than exploring the wider dimension of strategic management. Further studies should use additional resources to promote a better understanding of how priorities and needs may vary across organisational sectors, and, as suggested, depending on the maturity level of organisations. This should include a focus on the role of leadership in promoting a culture of organisational resilience, that have not been analysed at all in the state-of-art. Finally, for a matter of feasibility, this study focused on specific aspects of business continuity more than including a wider reference to part of the management process, including recovery. We would argue that new studies focused on the use of EEW and their applicability in complex scenarios should be conducted systematically to understand better possible differences between institutional and cultural contexts, supporting the creation of safer societies in the future.

# Chapter 8. Conclusions and Final Remarks

## 8.1 Main findings

The present report introduces the final dissertation report of the PhD project of the author, *“Investigating the cross-disciplinary components of earthquake early warning systems”*.

Chapter 2 describes in detail the basic functioning principle of EEW and provides a thorough description of the EEW systems and their relevant state-of-the-art algorithms currently operating around the world.

In summary, Earthquake Early Warnings are tools already operating in different areas of the world that are heavily affected by earthquakes. The EEW algorithms equipped in the seismic networks are capable of providing highly accurate real-time estimations of the earthquake’s source parameters (magnitude and location), and thus reliable estimates of ground motion shaking (or Intensity Measures) at different target points of interest, by adopting Real-time Ground Motion Prediction Models (e.g., the RTPSHA approach proposed by Iervolino et al. 2009). Then, the estimates of IMs available before the arrival of the earthquake, allow structural-earthquake engineers for the design of applications aiming for the protection and assessment of structures in real-time and, if feasible, for the evacuation of people from buildings if necessary. The technical review presented in this chapter represents strong evidence for the technical and engineering contents of this project, the design of two applications that are based in the information given by an EEW system.

Chapter 3 refers to the review of the social-organisational components of EEW. This was not a task that was initially thought to be addressed, but as the project advanced, it was recognised the high importance of the integration of the social, behavioural and organisational domains in an EEW study.

Chapter 3 breaks down the interactions between the technical and socio-organisational elements of EEW in the public and private sector, looking at four countries where EEW systems are operating, with different levels of maturity. Italy, California, Japan and Mexico were the benchmark case-studies considered to understand the local context and the technical details of each system. To this aim, four categories that describe the challenges for effective EEW in the socio-organisational domains were defined to support the understanding of the state-of-art for each case: Operational, Political and Governance, Social and Behavioural, and Organisational Sphere.

The analysis of each case-study and their relevant spheres followed an extensive and in-depth narrative literature review, that allowed the understanding of how each sphere can influence the efficiency and effectiveness of EEW in the socio-organisational context. In summary, it has been shown that despite the consistent technical progress of EEW across the case-studies, some of the cross-disciplinary aspects of the Operational, Political, Socio-Behavioural and Organisational spheres remain marginally integrated in practice, which lead to conclude that the idea of creating or having "people-centred EEW systems" is far from reality.

One of the major findings highlighted in this chapter is the lack of a strong cohesion between the official bodies that emit EEW and those organisations that might be beneficiated by a strong, reliable and accountable EEW. This also suggested that further efforts are required to promote legislations and policies about accountability and liability procedures, linked to the legal concerns triggered by the release of false alarms, for instance. The opens questions that emerge from this issue, such as *who is accountable for issuing alerts*?, and *What are the legal liabilities of disseminating earthquake warnings*?, motivated the further investigation of the topic, leading to the research and work showed in chapter 6 of this report.

Chapter number 4 introduced the preliminary results of the first application designed. This chapter proposed the use of MR dampers in smart passive mode (e.g., by changing their mechanical properties according to some IM of the incoming earthquake forecasted by an EEW system) to control just-in-time the dynamic characteristics of a structure, to achieve its optimal response against seismic forces. The change is supposed to happen only once, just before the ground shaking hits the target structure, according to an estimate of the anticipated spectral acceleration at the fundamental period of the hosting structure.

A storey-based building-specific loss estimation method was implemented to calibrate the MR damper control algorithm, so the losses expected, by setting a value of voltage into the damper, are the minimum according to the IM estimated by the EEW system. This methodology represents the first of its type, where an optimal algorithm for the control of structures is designed in terms of expected losses, allowing the combination of different improved performance requirements (e.g., deformation, acceleration, etc.), different from available studies in literature, where efforts focus only in the optimisation of a single engineering demand parameter.

In order to calibrate the algorithm, a set of 150 unscaled ground motion records was used as input for the nonlinear dynamic analysis of a simple three-degree-of-freedom shear frame fitted with one MR damper connecting the ground and first floor; for each ground motion record, the MR damper was fed with a range of voltage values (0-2.25 volts), always keeping the input voltage constant for the whole duration of the event. For each ground motion input, the value of the different Engineering Demand Parameters was recorded (for each voltage) and the optimal value of voltage leading to the minimum expected loss was computed.

The results from the analyses proved that, for the simplified structure considered, the algorithm derived for the calibration of MR dampers, based on the information provided by the EEW system, provides the best response of the structure subjected to earthquakes in comparison with traditional structural control systems (passive and semi-active).

Chapter 5 described the procedure followed for the calibration of Engineering Demand Parameters Prediction Equations, and their application on Real-Time Assessment of Building Response, based on the information provided by an EEW system. The new equations represent a change from traditional Intensity Measure Prediction equations, given that Intensity Measures, as Peak Ground Acceleration, have proven to be poor proxies for the estimation of building response and building damage due to earthquakes. The calibration was carried out by performing multilinear regressions on a large database containing the response of buildings in terms of Interstorey Drift Ratio (IDR) and Peak Floor Acceleration (PFA).

A simplified continuous model, consisting of a combination of a flexural beam and a shear beam, was adopted for the computation of Engineering Demand Parameters (IDR and PFA), for a broad variety of building typologies. By just modifying two parameters (the lateral stiffness ratio, $\alpha$, and the natural period of oscillation of the building, $T$), different lateral load resisting systems (from shear wall systems to moment resisting frames systems) and different height of buildings (from low-rise buildings to high-rise buildings) could be simulated. 45 different structures were modelled, considering three values of $\alpha$ and 15 natural periods of oscillation.

Numerical simulations were performed for the 45 structures, subjecting them to a set of 589 ground motions recorded in the Italian region. The criteria for the selection of the events was as follows: a) minimum magnitude of the event equal to 5 $M_w$, and b) epicentral distances shorter than 200km. At this point, the powerful advantages of the continuous model adopted were visible. A total of 53,010 analyses were carried out in a considerable short period of time. It is important to highlight that fast analyses were necessary as a large size of the database was essential for the calibration of the new Building Response Prediction Equations.

The results from the simulations, in terms of IDR and PFA, were collected and organised, so multilinear regressions could be performed for each EDP. A simplified functional form, proposed for the Italian region, was considered in this chapter. The coefficients given by the regression were statistically analysed (standard deviations, residuals and p-values) showing reliable results.

Once the equations were derived, for each EDP, a real-time simulation was implemented for the Campania region, in Italy. The efficiency of the new models was tested for the creation of exceedance probability curves (in terms of EDPs) and for the construction of real-time maps (in terms of EDPs, as well). The results of the simulation proved that the new proposed equations represent a powerful tool for the real-time evaluation of damage in buildings due to earthquakes and motivated for a future evolution of the application.

This chapter represents the first attempt for the application of Engineering Demand Prediction Equations for the real-time assessment of buildings, conditioned to the estimates given by Earthquake Early Warnings.

Chapter 7 investigates how EEW can be integrated into practices of organisational resilience, business continuity and disaster risk reduction. In particular, this chapter explores what information and training are needed by the public and the private sector in order to respond and adapt more effectively to the dissemination of EEW, improving when possible organisational practices.

A mixed method approach is used to analyse the case study of Mexico City (Mexico), an area at high seismic risk due to the combination of high seismic hazard, social and physical exposure and vulnerability. The dataset includes evidence from 15 semi-structured interviews with representatives of the public and private sectors (e.g., schools, governments, industry), together with 78 valid questionnaires compiled by local organisations, including civil protection, education institutions, and enterprises. The structure of the questionnaires and interviews has been grounded in the academic state-of-the-art and in standards such as the ones by the International Standardisation Organisation. The Likert-scale introduced in Chapter 6 is implemented for the development of the questionnaires, as a preliminary pilot study in Mexico City showed that different available Likert-scales would leave gaps in the responses of all those who could answer the questionnaire. The scale proposed in Chapter 6 allows for the adaptation of questions and answers to a local context, bringing more clarity and insight about all the data collected.

The results highlight a discrepancy between well-established technical methods/algorithms and their integration in organisational resilience, business continuity management, and disaster risk reduction. The discussion points out gaps in three domains: governance, accountability and liability; standardisation of plans and procedures; training and education. The conclusions propose new steps for developing new practices of EEW for complex scenarios while highlighting open challenges for future researches.

### 8.1.1 Final remarks

This thesis represents the first attempt to assess the potential benefits that EEW might incorporate to organisational resilience, supplying researchers and practitioners with a framework that can be adapted to different cities/regions/countries where EEW are currently available or operational.

This thesis has presented a wide overview of EEW systems in a technical (e.g., seismological and engineering) and social perspectives. What can be drawn in general terms is that EEW has the maturity and potential to offer reliable warnings to al those who might receive an alarm, but many difficulties (exclusive to every city/region/country where the systems operate) exist for the accomplishment of their complete/full applications in the socio-organisational context.

This thesis also promotes the, so-far very limited, engineering applicability of EEW. Chapter 4 and 5 introduce two novel real-time applications which aim at motivating different researchers to invest efforts in this field. The two applications presented show the potential that EEW can offer for the activation of automatic actions which main goal is the assessment of likely damage and/or the mitigation of losses, given the estimates provided by the systems. Developing automatic actions based on the estimates provided by EEW represent an opportunity for the reduction of economic and human losses in those places where lead times do not allow the evacuation or the activation of human responses. Even in those areas where lead times are large enough, automatic procedures can cover those functions carried by individuals, conceding important seconds for the implementation of different protection measures by those who receive the alarm.

In the social spectrum, chapter 3 and 7 provide a clear picture of the social-organisational barriers that currently avoid the applicability of the potential benefits that EEW can bring into the socio-organisational cohort. The work contained in these chapters indicate the tools that might be required to improve such applicability. The results and recommendation of these chapters might be useful for those EEW systems that have advanced technology but have not been successful (or have never implemented) at boosting the benefits at the socio-organisational level. PRESTo, in Italy, is a good example; the system is state-of-the art, even implemented in other countries around the world given its reliability, but its implementation in the Italian society has never been put in place. Mexico on the other hand has the experience related to EEW for more than 30 years, but the lessons learned have not been feedbacked socio-organisationally.

One of the main goals of this thesis was to study the interdisciplinarity of EEW, from a technical and a social point of view. It is not common to find in the academic literature studies on natural hazards that combine the efforts from these two fields of expertise. This project has demonstrated that such approach is feasible, and that the results offer wider perspectives for a most exhaustive comprehension of natural hazards, or EEW in this particular case.

## 8.2 Future Work

### 8.2.1 Integration of Semi-Active Structural Control with Earthquake Early Warnings

Given that the case-study adopted is very unique and cannot represent the behaviour of different configurations and types of buildings, future work in this matter aims to extend the study modifying the numerical model into a Single Degree of Freedom System that can account for different heights and different levels of non-linearity. By doing this, the expectation is to obtain different responses of the structure, according to the value of damping added to the structure by the MR damper (by increasing or decreasing the electrical current induced to the damper), and given the level of non-linearity adopted in the building. The model of the SDOF with different values of natural period of oscillation and different levels of non-linearity has been already designed and implemented by different authors (e.g., Karavasilis and Seo, 2011). In addition, the scaled MR damper adopted for the chapter can be replaced for a full-scale MR damper (e.g., Cha et al., 2014), able to create damping forces up to 200kN, different from the maximum damping able in the small MR damper, 3kN.

### 8.2.2 Real-Time Assessment of Building Response for Earthquake Early Warning Applications

For the second application described in the chapter, the following improvements are proposed for further developments:

Adopting an inelastic simplified model for the numerical simulations. The model used for the computation of EDPs carries out elastic analyses, which provides conservative responses of the building in terms of IDR or PFA. By adding flexural springs and shear springs in the correspondent beams (e.g., Xiong et al., 2016), non-linear behaviours of the structure can be computed (Figure 50).

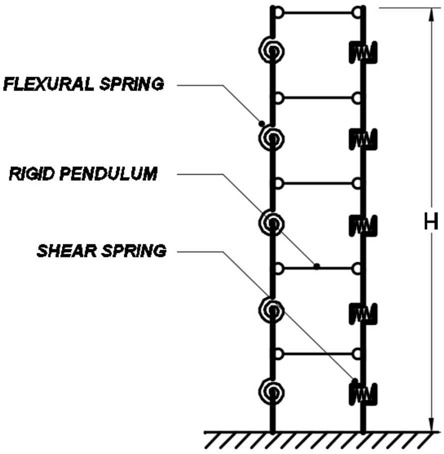

*Figure 50. Non-linear Simplified Model proposed by Xiong et al. (2016).*

The creation of 3 Dimensions EDPs maps, rather than 2D (chapter 5.6), where the expected EDP is estimated not only for a specific area of interest, but for every single storey within a selected building stock (Figure 51). These maps could help for the implementation of safety measures in buildings. For instance, warnings to occupants based on human comfort or control of elevators in tall buildings, are applications that can be designed based on the predictions of PFA. The maps could also be used after the event for the classification of damage within each structure, labelling the in-safety of each building according to the damage computed in the 3D map.

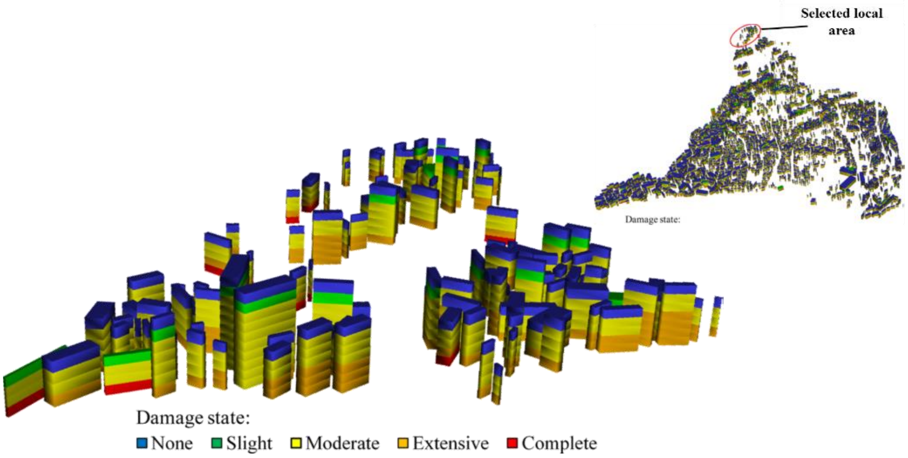

*Figure 51. 3D map of building damage*

### 8.2.3 Integrating earthquake early warnings into business continuity and organisational resilience: lessons learned from Mexico City.

First of all, as indicated in Chapter 7, the number of organisations interviewed and that answered the questionnaire represent a limited sample of Mexico City, and Mexico as a whole. Perhaps more needs and requests might appear if more local organisations in Mexico City provide their thoughts and perspectives about how to incorporate and use EEW for business continuity practices and operational resilience. In addition, Mexico City is not the only region in the country that receives EEW; performing the same study in any of the other six states that receive alarms in Mexico is an attractive research effort that might yield different answers, or reinforce the findings and results of Chapter 7.

It is then clear that a potential work that can be done is the application of the approach proposed in Chapter 7 to other countries where EEW is currently available or operational. The different socio-organisational arrangements of other nations definitely would show different results and new knowledge that can work as feedback for other systems around the world to improve business continuity and operational resilience.

# 9. Publications and awards

## Publications

**Velazquez, O**., Galasso, C., and Duffour, P. (2017). A loss-based control algorithm for magnetorheological dampers combined with earthquake early warning. *16 World Conference on Earthquake Engineering – Proceedings.*

**Velazquez, O**., Pescaroli, G., and Galasso, C. (2020). A review of the technical and socio-organisational components of earthquake early warning systems. *Frontiers in Earth Science 8 (2020): 445.*

Pescaroli, G., **Velazquez, O**., Alcantara-Ayala, I., Galasso, C., Kostkova, P., Alexander, D. (2020). A Likert scale-based model for benchmarking operational capacity, organizational resilience, and disaster risk reduction. *International Journal of Disaster Risk Science.*

Salas, C., Ps, O., Sanchez, G., Velez, J., Todd, N., **Velazquez, O.**, Alvarez-Monjaras., M. (2020). Toolkit de Estrategias de Afrontamiento (in Spanish) [In press]. *Publicaciones Universidad Iberoamericana.*

## Awards

2015-19. Scholarship awarded by CONACYT-Mexico for PhD studies.

2015. Student/Young award granted by the ECGS & ESC/EAEE Joint Workshop: Earthquake and Induced Multi-Risk Early Warning and Rapid Response’, Luxembourg 2015.

2016. Grant awarded by the Fukushima Prefecture Government, for a Fieldtrip to the area affected by the Fukushima- Daiichi nuclear power plant incident in the Fukushima Prefecture, on the 5th Anniversary of the Tohoku Earthquake.

2017. UCL Grand Challenges Doctoral Students' Small Grants Scheme. Fieldtrip to the area affected by the 2017 Amatrice sequence. Central Italy.

2019-20. EEFIT Research Grant. Integrating socio-behavioral and technical components of Earthquake Early Warnings. Caste-study, Mexico City.

2019-20. British Academy – Leverhulme Small Research Grant. Integrating socio-behavioral and technical components of Earthquake Early Warnings. Caste-study, Mexico City.

2019. PhD student Annual Prize for outstanding contribution to the UCL Institute for Risk and Disaster Reduction.

## Outreach

2017. Live interview on Mexican Television (RT) to discuss the performance of the Mexican Earthquake Early Warning System during the September 2017 Earthquakes.

# 10. Appendix 1

Appendix #1 contains the values of the coefficients obtained after performing the nonlinear regression analysis in Chapter 5. 3 tables for each EDP (MIDR, IDR, and PFA) have been included for the reader, corresponding to the 3 values of $\alpha$ used in the study (0.1, 8, and 30). For simplicity, only 10 values of *z* (the normalised height of the structure) have been included for the tables of IDR and PFA (the rest of the values can be provided upon request).

Table 24, Table 25, and Table 26 summarise the coefficients obtained for MIDR.

*Table 24. Coefficients for Maximum Interstorey Drift Ratio, α=0.1 (εσ is the total standard deviation)*

| Period (s) | b1 | b2 | b3 | b4 | b5 | b6 | εσ |
|---|---|---|---|---|---|---|---|
| **0.1** | -2.030 | 0.578 | -2.113 | -14.433 | 0.275 | 0.214 | 0.408 |
| **0.2** | -2.130 | 0.617 | -2.014 | -16.024 | 0.305 | 0.242 | 0.406 |
| **0.3** | -2.758 | 0.658 | -1.781 | -13.815 | 0.315 | 0.271 | 0.378 |
| **0.4** | -3.177 | 0.698 | -1.659 | -13.329 | 0.306 | 0.274 | 0.373 |
| **0.5** | -3.522 | 0.735 | -1.584 | -13.112 | 0.324 | 0.261 | 0.371 |
| **0.75** | -4.246 | 0.812 | -1.452 | -11.376 | 0.383 | 0.269 | 0.368 |
| **1** | -4.656 | 0.855 | -1.399 | -10.751 | 0.417 | 0.291 | 0.365 |
| **1.5** | -5.154 | 0.897 | -1.306 | -10.384 | 0.413 | 0.302 | 0.372 |
| **2** | -5.453 | 0.917 | -1.257 | -9.338 | 0.390 | 0.295 | 0.369 |
| **2.5** | -5.521 | 0.909 | -1.233 | -9.288 | 0.366 | 0.294 | 0.364 |
| **3** | -5.615 | 0.918 | -1.238 | -9.717 | 0.367 | 0.278 | 0.364 |
| **3.5** | -5.690 | 0.927 | -1.254 | -10.082 | 0.366 | 0.274 | 0.362 |
| **4** | -5.745 | 0.929 | -1.260 | -10.018 | 0.359 | 0.270 | 0.358 |
| **4.5** | -5.808 | 0.936 | -1.272 | -10.069 | 0.360 | 0.260 | 0.359 |
| **5** | -5.894 | 0.946 | -1.281 | -9.988 | 0.369 | 0.265 | 0.360 |

*Table 25. Coefficients for Maximum Interstorey Drift Ratio, α=8 (εσ is the total standard deviation)*

| Period (s) | b1 | b2 | b3 | b4 | b5 | b6 | εσ |
|---|---|---|---|---|---|---|---|
| **0.1** | -2.125 | 0.582 | -2.079 | -14.189 | 0.280 | 0.216 | 0.403 |
| **0.2** | -2.214 | 0.620 | -1.988 | -15.694 | 0.306 | 0.241 | 0.400 |
| **0.3** | -2.761 | 0.652 | -1.769 | -13.530 | 0.316 | 0.264 | 0.370 |
| **0.4** | -3.103 | 0.689 | -1.679 | -13.212 | 0.325 | 0.266 | 0.364 |
| **0.5** | -3.381 | 0.721 | -1.619 | -13.034 | 0.338 | 0.256 | 0.367 |
| **0.75** | -4.032 | 0.785 | -1.483 | -11.452 | 0.378 | 0.274 | 0.364 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **1** | -4.444 | 0.823 | -1.410 | -10.188 | 0.399 | 0.295 | 0.364 |
| **1.5** | -4.891 | 0.866 | -1.336 | -10.639 | 0.403 | 0.300 | 0.367 |
| **2** | -5.199 | 0.896 | -1.303 | -9.800 | 0.392 | 0.292 | 0.369 |
| **2.5** | -5.332 | 0.902 | -1.286 | -9.550 | 0.390 | 0.289 | 0.369 |
| **3** | -5.450 | 0.908 | -1.274 | -9.692 | 0.410 | 0.296 | 0.373 |
| **3.5** | -5.513 | 0.914 | -1.287 | -10.189 | 0.404 | 0.297 | 0.374 |
| **4** | -5.588 | 0.916 | -1.274 | -10.061 | 0.389 | 0.294 | 0.371 |
| **4.5** | -5.762 | 0.933 | -1.258 | -9.483 | 0.391 | 0.292 | 0.372 |
| **5** | -5.906 | 0.952 | -1.260 | -9.454 | 0.381 | 0.287 | 0.373 |

*Table 26. Coefficients for Maximum Interstorey Drift Ratio, α=30 (εσ is the total standard deviation)*

| Period (s) | b1 | b2 | b3 | b4 | b5 | b6 | εσ |
|---|---|---|---|---|---|---|---|
| **0.1** | -2.117 | 0.586 | -2.063 | -14.093 | 0.283 | 0.218 | 0.400 |
| **0.2** | -2.208 | 0.622 | -1.970 | -15.435 | 0.306 | 0.242 | 0.398 |
| **0.3** | -2.752 | 0.653 | -1.755 | -13.347 | 0.318 | 0.265 | 0.372 |
| **0.4** | -3.107 | 0.694 | -1.669 | -13.086 | 0.326 | 0.270 | 0.367 |
| **0.5** | -3.397 | 0.724 | -1.598 | -12.883 | 0.332 | 0.258 | 0.369 |
| **0.75** | -4.139 | 0.803 | -1.465 | -11.237 | 0.381 | 0.272 | 0.366 |
| **1** | -4.494 | 0.835 | -1.402 | -10.586 | 0.406 | 0.300 | 0.362 |
| **1.5** | -5.034 | 0.887 | -1.315 | -10.411 | 0.407 | 0.300 | 0.368 |
| **2** | -5.344 | 0.916 | -1.283 | -9.652 | 0.392 | 0.291 | 0.370 |
| **2.5** | -5.516 | 0.922 | -1.249 | -9.357 | 0.390 | 0.297 | 0.370 |
| **3** | -5.591 | 0.924 | -1.246 | -9.964 | 0.391 | 0.291 | 0.372 |
| **3.5** | -5.722 | 0.937 | -1.245 | -10.094 | 0.392 | 0.289 | 0.374 |
| **4** | -5.845 | 0.948 | -1.241 | -9.790 | 0.382 | 0.286 | 0.373 |
| **4.5** | -5.962 | 0.960 | -1.242 | -9.800 | 0.375 | 0.283 | 0.376 |
| **5** | -6.014 | 0.964 | -1.249 | -10.045 | 0.371 | 0.282 | 0.372 |

Table 27, Table 28, and Table 29 show the coefficients computed for IDR. 10 values of *z* have been selected for illustrative purposes.

*Table 27. Coefficients for Interstorey Drift Ratio, α=0.1 (εσ is the total standard deviation)*

| | **Period (s)** | **b1** | **b2** | **b3** | **b4** | **b5** | **b6** | **εσ** |
|---|---|---|---|---|---|---|---|---|
| **z=0.05** | 0.1 | -3.000 | 0.583 | -2.081 | -14.233 | 0.280 | 0.216 | 0.403 |
| | 0.2 | -3.118 | 0.623 | -1.984 | -15.737 | 0.308 | 0.243 | 0.402 |
| | 0.3 | -3.750 | 0.667 | -1.762 | -13.660 | 0.314 | 0.273 | 0.377 |
| | 0.4 | -4.154 | 0.703 | -1.637 | -12.996 | 0.299 | 0.271 | 0.372 |
| | 0.5 | -4.478 | 0.739 | -1.569 | -12.888 | 0.320 | 0.260 | 0.371 |
| | 0.75 | -5.118 | 0.807 | -1.455 | -11.140 | 0.391 | 0.266 | 0.360 |
| | 1 | -5.438 | 0.841 | -1.418 | -10.599 | 0.428 | 0.291 | 0.360 |
| | 1.5 | -5.794 | 0.866 | -1.340 | -10.142 | 0.405 | 0.296 | 0.361 |
| | 2 | -6.000 | 0.875 | -1.299 | -9.183 | 0.376 | 0.290 | 0.352 |
| | 2.5 | -5.944 | 0.856 | -1.293 | -9.412 | 0.358 | 0.284 | 0.348 |
| | 3 | -5.955 | 0.855 | -1.305 | -9.720 | 0.351 | 0.271 | 0.353 |
| | 3.5 | -5.979 | 0.863 | -1.340 | -10.564 | 0.352 | 0.274 | 0.351 |
| | 4 | -6.011 | 0.867 | -1.351 | -10.512 | 0.348 | 0.271 | 0.347 |
| | 4.5 | -6.060 | 0.875 | -1.367 | -10.805 | 0.357 | 0.263 | 0.345 |
| | 5 | -6.103 | 0.877 | -1.372 | -10.270 | 0.359 | 0.264 | 0.343 |
| **z=0.10** | 0.1 | -2.709 | 0.582 | -2.084 | -14.250 | 0.279 | 0.216 | 0.404 |
| | 0.2 | -2.826 | 0.623 | -1.987 | -15.765 | 0.308 | 0.243 | 0.402 |
| | 0.3 | -3.460 | 0.666 | -1.764 | -13.696 | 0.314 | 0.273 | 0.378 |
| | 0.4 | -3.873 | 0.704 | -1.638 | -13.053 | 0.300 | 0.271 | 0.373 |
| | 0.5 | -4.204 | 0.740 | -1.569 | -12.958 | 0.320 | 0.261 | 0.372 |
| | 0.75 | -4.871 | 0.811 | -1.450 | -11.205 | 0.389 | 0.266 | 0.363 |
| | 1 | -5.209 | 0.847 | -1.410 | -10.660 | 0.429 | 0.292 | 0.362 |
| | 1.5 | -5.605 | 0.876 | -1.327 | -10.185 | 0.410 | 0.297 | 0.364 |
| | 2 | -5.844 | 0.889 | -1.281 | -9.161 | 0.377 | 0.291 | 0.356 |
| | 2.5 | -5.808 | 0.870 | -1.272 | -9.374 | 0.360 | 0.287 | 0.351 |
| | 3 | -5.835 | 0.871 | -1.282 | -9.720 | 0.353 | 0.274 | 0.355 |
| | 3.5 | -5.874 | 0.880 | -1.314 | -10.548 | 0.354 | 0.275 | 0.353 |
| | 4 | -5.914 | 0.884 | -1.323 | -10.404 | 0.346 | 0.271 | 0.351 |
| | 4.5 | -5.969 | 0.892 | -1.339 | -10.755 | 0.354 | 0.263 | 0.349 |
| | 5 | -6.017 | 0.895 | -1.345 | -10.245 | 0.357 | 0.263 | 0.347 |
| **z=0.20** | 0.1 | -2.430 | 0.581 | -2.090 | -14.289 | 0.278 | 0.216 | 0.405 |
| | 0.2 | -2.543 | 0.622 | -1.993 | -15.827 | 0.307 | 0.243 | 0.403 |
| | 0.3 | -3.182 | 0.666 | -1.768 | -13.766 | 0.315 | 0.273 | 0.378 |
| | 0.4 | -3.610 | 0.705 | -1.640 | -13.176 | 0.300 | 0.274 | 0.375 |
| | 0.5 | -3.961 | 0.744 | -1.567 | -13.070 | 0.319 | 0.263 | 0.374 |
| | 0.75 | -4.684 | 0.821 | -1.438 | -11.340 | 0.383 | 0.267 | 0.369 |
| | 1 | -5.068 | 0.861 | -1.393 | -10.838 | 0.428 | 0.293 | 0.366 |
| | 1.5 | -5.551 | 0.900 | -1.301 | -10.420 | 0.419 | 0.298 | 0.370 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2 | -5.868 | 0.921 | -1.245 | -9.221 | 0.382 | 0.291 | 0.365 |
| | 2.5 | -5.881 | 0.906 | -1.226 | -9.429 | 0.359 | 0.291 | 0.361 |
| | 3 | -5.951 | 0.909 | -1.230 | -9.772 | 0.356 | 0.280 | 0.362 |
| | 3.5 | -6.017 | 0.920 | -1.259 | -10.515 | 0.354 | 0.275 | 0.361 |
| | 4 | -6.067 | 0.922 | -1.263 | -10.276 | 0.347 | 0.270 | 0.359 |
| | 4.5 | -6.133 | 0.932 | -1.280 | -10.610 | 0.346 | 0.265 | 0.360 |
| | 5 | -6.191 | 0.937 | -1.289 | -10.331 | 0.348 | 0.261 | 0.358 |
| **z=0.30** | 0.1 | -2.278 | 0.580 | -2.096 | -14.327 | 0.277 | 0.215 | 0.405 |
| | 0.2 | -2.389 | 0.621 | -1.998 | -15.883 | 0.307 | 0.243 | 0.404 |
| | 0.3 | -3.031 | 0.664 | -1.771 | -13.815 | 0.316 | 0.274 | 0.378 |
| | 0.4 | -3.472 | 0.706 | -1.642 | -13.295 | 0.301 | 0.276 | 0.376 |
| | 0.5 | -3.842 | 0.747 | -1.567 | -13.182 | 0.320 | 0.265 | 0.376 |
| | 0.75 | -4.632 | 0.831 | -1.427 | -11.468 | 0.375 | 0.267 | 0.377 |
| | 1 | -5.064 | 0.877 | -1.376 | -11.096 | 0.424 | 0.293 | 0.374 |
| | 1.5 | -5.644 | 0.926 | -1.271 | -10.620 | 0.427 | 0.298 | 0.379 |
| | 2 | -6.011 | 0.954 | -1.213 | -9.411 | 0.388 | 0.287 | 0.376 |
| | 2.5 | -6.098 | 0.944 | -1.184 | -9.345 | 0.366 | 0.291 | 0.372 |
| | 3 | -6.183 | 0.947 | -1.182 | -9.715 | 0.361 | 0.282 | 0.370 |
| | 3.5 | -6.233 | 0.951 | -1.202 | -10.202 | 0.355 | 0.271 | 0.368 |
| | 4 | -6.280 | 0.951 | -1.209 | -10.072 | 0.351 | 0.267 | 0.363 |
| | 4.5 | -6.324 | 0.954 | -1.225 | -10.134 | 0.353 | 0.266 | 0.362 |
| | 5 | -6.361 | 0.960 | -1.250 | -10.202 | 0.352 | 0.262 | 0.359 |
| **z=0.40** | 0.1 | -2.182 | 0.579 | -2.101 | -14.360 | 0.277 | 0.215 | 0.406 |
| | 0.2 | -2.291 | 0.620 | -2.003 | -15.929 | 0.306 | 0.242 | 0.404 |
| | 0.3 | -2.934 | 0.663 | -1.773 | -13.827 | 0.316 | 0.273 | 0.379 |
| | 0.4 | -3.382 | 0.706 | -1.645 | -13.394 | 0.303 | 0.277 | 0.377 |
| | 0.5 | -3.769 | 0.749 | -1.568 | -13.265 | 0.321 | 0.267 | 0.378 |
| | 0.75 | -4.616 | 0.841 | -1.421 | -11.619 | 0.367 | 0.269 | 0.386 |
| | 1 | -5.088 | 0.891 | -1.362 | -11.437 | 0.412 | 0.294 | 0.384 |
| | 1.5 | -5.746 | 0.949 | -1.248 | -10.898 | 0.429 | 0.299 | 0.390 |
| | 2 | -6.139 | 0.977 | -1.185 | -9.819 | 0.397 | 0.283 | 0.385 |
| | 2.5 | -6.290 | 0.977 | -1.157 | -9.403 | 0.382 | 0.287 | 0.380 |
| | 3 | -6.424 | 0.985 | -1.154 | -9.273 | 0.370 | 0.279 | 0.378 |
| | 3.5 | -6.421 | 0.975 | -1.163 | -9.602 | 0.363 | 0.268 | 0.377 |
| | 4 | -6.423 | 0.965 | -1.169 | -9.718 | 0.356 | 0.271 | 0.371 |
| | 4.5 | -6.450 | 0.964 | -1.184 | -9.778 | 0.346 | 0.266 | 0.365 |
| | 5 | -6.489 | 0.970 | -1.209 | -9.590 | 0.339 | 0.258 | 0.362 |
| **z=0.50** | 0.1 | -2.118 | 0.579 | -2.105 | -14.386 | 0.276 | 0.215 | 0.407 |
| | 0.2 | -2.224 | 0.619 | -2.007 | -15.967 | 0.306 | 0.242 | 0.405 |
| | 0.3 | -2.865 | 0.662 | -1.776 | -13.825 | 0.316 | 0.273 | 0.378 |
| | 0.4 | -3.310 | 0.705 | -1.649 | -13.432 | 0.304 | 0.277 | 0.377 |
| | 0.5 | -3.696 | 0.748 | -1.572 | -13.326 | 0.323 | 0.266 | 0.377 |
| | 0.75 | -4.556 | 0.842 | -1.425 | -11.663 | 0.369 | 0.271 | 0.387 |
| | 1 | -5.056 | 0.895 | -1.362 | -11.420 | 0.403 | 0.295 | 0.390 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1.5 | -5.736 | 0.956 | -1.246 | -11.087 | 0.423 | 0.301 | 0.395 |
| | 2 | -6.151 | 0.987 | -1.181 | -9.890 | 0.397 | 0.285 | 0.389 |
| | 2.5 | -6.305 | 0.985 | -1.149 | -9.382 | 0.386 | 0.289 | 0.385 |
| | 3 | -6.520 | 1.007 | -1.147 | -9.257 | 0.382 | 0.273 | 0.385 |
| | 3.5 | -6.500 | 0.994 | -1.160 | -9.612 | 0.370 | 0.268 | 0.385 |
| | 4 | -6.506 | 0.984 | -1.163 | -9.448 | 0.354 | 0.261 | 0.378 |
| | 4.5 | -6.541 | 0.984 | -1.178 | -9.618 | 0.341 | 0.262 | 0.375 |
| | 5 | -6.589 | 0.985 | -1.187 | -9.471 | 0.335 | 0.259 | 0.371 |
| **z=0.60** | 0.1 | -2.076 | 0.578 | -2.109 | -14.406 | 0.275 | 0.214 | 0.407 |
| | 0.2 | -2.180 | 0.618 | -2.010 | -15.993 | 0.306 | 0.242 | 0.405 |
| | 0.3 | -2.816 | 0.660 | -1.778 | -13.825 | 0.316 | 0.272 | 0.378 |
| | 0.4 | -3.252 | 0.702 | -1.653 | -13.403 | 0.305 | 0.276 | 0.375 |
| | 0.5 | -3.622 | 0.743 | -1.577 | -13.266 | 0.324 | 0.265 | 0.375 |
| | 0.75 | -4.437 | 0.831 | -1.433 | -11.523 | 0.376 | 0.270 | 0.379 |
| | 1 | -4.917 | 0.881 | -1.371 | -11.021 | 0.411 | 0.294 | 0.379 |
| | 1.5 | -5.569 | 0.941 | -1.262 | -10.706 | 0.417 | 0.302 | 0.390 |
| | 2 | -5.964 | 0.972 | -1.204 | -9.634 | 0.390 | 0.292 | 0.386 |
| | 2.5 | -6.086 | 0.967 | -1.172 | -9.433 | 0.376 | 0.296 | 0.380 |
| | 3 | -6.269 | 0.984 | -1.167 | -9.595 | 0.377 | 0.282 | 0.380 |
| | 3.5 | -6.330 | 0.986 | -1.180 | -10.104 | 0.375 | 0.272 | 0.377 |
| | 4 | -6.372 | 0.984 | -1.183 | -10.011 | 0.364 | 0.262 | 0.373 |
| | 4.5 | -6.411 | 0.986 | -1.202 | -10.217 | 0.357 | 0.259 | 0.372 |
| | 5 | -6.497 | 0.994 | -1.213 | -10.059 | 0.359 | 0.260 | 0.372 |
| **z=0.70** | 0.1 | -2.050 | 0.578 | -2.111 | -14.420 | 0.275 | 0.214 | 0.408 |
| | 0.2 | -2.152 | 0.618 | -2.012 | -16.011 | 0.305 | 0.242 | 0.405 |
| | 0.3 | -2.784 | 0.659 | -1.780 | -13.820 | 0.316 | 0.272 | 0.378 |
| | 0.4 | -3.212 | 0.700 | -1.656 | -13.366 | 0.306 | 0.275 | 0.374 |
| | 0.5 | -3.569 | 0.739 | -1.581 | -13.189 | 0.324 | 0.263 | 0.373 |
| | 0.75 | -4.338 | 0.821 | -1.442 | -11.447 | 0.380 | 0.269 | 0.373 |
| | 1 | -4.786 | 0.868 | -1.384 | -10.851 | 0.416 | 0.293 | 0.371 |
| | 1.5 | -5.377 | 0.921 | -1.282 | -10.534 | 0.416 | 0.304 | 0.381 |
| | 2 | -5.752 | 0.951 | -1.228 | -9.498 | 0.388 | 0.296 | 0.380 |
| | 2.5 | -5.890 | 0.948 | -1.188 | -9.323 | 0.363 | 0.301 | 0.379 |
| | 3 | -6.033 | 0.961 | -1.188 | -9.885 | 0.369 | 0.287 | 0.378 |
| | 3.5 | -6.144 | 0.974 | -1.202 | -10.430 | 0.367 | 0.275 | 0.378 |
| | 4 | -6.209 | 0.977 | -1.206 | -10.465 | 0.358 | 0.266 | 0.375 |
| | 4.5 | -6.284 | 0.984 | -1.221 | -10.561 | 0.358 | 0.258 | 0.375 |
| | 5 | -6.387 | 0.995 | -1.227 | -10.576 | 0.363 | 0.260 | 0.375 |
| **z=0.80** | 0.1 | -2.036 | 0.578 | -2.112 | -14.429 | 0.275 | 0.214 | 0.408 |
| | 0.2 | -2.137 | 0.618 | -2.013 | -16.020 | 0.305 | 0.242 | 0.405 |
| | 0.3 | -2.766 | 0.658 | -1.781 | -13.817 | 0.315 | 0.271 | 0.378 |
| | 0.4 | -3.188 | 0.698 | -1.658 | -13.342 | 0.306 | 0.274 | 0.374 |
| | 0.5 | -3.538 | 0.736 | -1.583 | -13.139 | 0.324 | 0.262 | 0.372 |
| | 0.75 | -4.277 | 0.815 | -1.449 | -11.403 | 0.382 | 0.269 | 0.369 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | -4.701 | 0.860 | -1.394 | -10.784 | 0.417 | 0.292 | 0.367 |
| | 1.5 | -5.233 | 0.905 | -1.297 | -10.447 | 0.414 | 0.303 | 0.375 |
| | 2 | -5.566 | 0.930 | -1.246 | -9.392 | 0.390 | 0.296 | 0.373 |
| | 2.5 | -5.665 | 0.925 | -1.215 | -9.299 | 0.365 | 0.298 | 0.370 |
| | 3 | -5.794 | 0.936 | -1.215 | -9.742 | 0.367 | 0.281 | 0.370 |
| | 3.5 | -5.894 | 0.949 | -1.230 | -10.244 | 0.365 | 0.276 | 0.370 |
| | 4 | -5.973 | 0.955 | -1.236 | -10.277 | 0.356 | 0.270 | 0.369 |
| | 4.5 | -6.057 | 0.965 | -1.251 | -10.422 | 0.355 | 0.262 | 0.372 |
| | 5 | -6.164 | 0.977 | -1.256 | -10.387 | 0.361 | 0.265 | 0.374 |
| **z=0.90** | 0.1 | -2.031 | 0.578 | -2.113 | -14.432 | 0.275 | 0.214 | 0.408 |
| | 0.2 | -2.131 | 0.617 | -2.014 | -16.024 | 0.305 | 0.242 | 0.406 |
| | 0.3 | -2.759 | 0.658 | -1.781 | -13.816 | 0.315 | 0.271 | 0.378 |
| | 0.4 | -3.178 | 0.698 | -1.658 | -13.331 | 0.306 | 0.274 | 0.374 |
| | 0.5 | -3.524 | 0.735 | -1.584 | -13.115 | 0.324 | 0.261 | 0.371 |
| | 0.75 | -4.250 | 0.812 | -1.452 | -11.380 | 0.383 | 0.269 | 0.368 |
| | 1 | -4.663 | 0.856 | -1.399 | -10.756 | 0.417 | 0.291 | 0.365 |
| | 1.5 | -5.166 | 0.898 | -1.304 | -10.397 | 0.414 | 0.302 | 0.372 |
| | 2 | -5.470 | 0.919 | -1.255 | -9.347 | 0.390 | 0.295 | 0.369 |
| | 2.5 | -5.543 | 0.912 | -1.230 | -9.288 | 0.366 | 0.295 | 0.365 |
| | 3 | -5.644 | 0.921 | -1.235 | -9.719 | 0.367 | 0.278 | 0.365 |
| | 3.5 | -5.723 | 0.930 | -1.250 | -10.106 | 0.366 | 0.274 | 0.363 |
| | 4 | -5.784 | 0.934 | -1.255 | -10.055 | 0.358 | 0.270 | 0.360 |
| | 4.5 | -5.852 | 0.941 | -1.267 | -10.114 | 0.359 | 0.260 | 0.361 |
| | 5 | -5.943 | 0.952 | -1.276 | -10.061 | 0.368 | 0.265 | 0.363 |
| **z=1.00** | 0.1 | -2.030 | 0.578 | -2.113 | -14.433 | 0.275 | 0.214 | 0.408 |
| | 0.2 | -2.130 | 0.617 | -2.014 | -16.024 | 0.305 | 0.242 | 0.406 |
| | 0.3 | -2.758 | 0.658 | -1.781 | -13.815 | 0.315 | 0.271 | 0.378 |
| | 0.4 | -3.177 | 0.698 | -1.659 | -13.329 | 0.306 | 0.274 | 0.373 |
| | 0.5 | -3.522 | 0.735 | -1.584 | -13.112 | 0.324 | 0.261 | 0.371 |
| | 0.75 | -4.246 | 0.812 | -1.452 | -11.376 | 0.383 | 0.269 | 0.368 |
| | 1 | -4.656 | 0.855 | -1.399 | -10.751 | 0.417 | 0.291 | 0.365 |
| | 1.5 | -5.154 | 0.897 | -1.306 | -10.384 | 0.413 | 0.302 | 0.372 |
| | 2 | -5.453 | 0.917 | -1.257 | -9.338 | 0.390 | 0.295 | 0.369 |
| | 2.5 | -5.521 | 0.909 | -1.233 | -9.288 | 0.366 | 0.294 | 0.364 |
| | 3 | -5.615 | 0.918 | -1.238 | -9.717 | 0.367 | 0.278 | 0.364 |
| | 3.5 | -5.690 | 0.927 | -1.254 | -10.082 | 0.366 | 0.274 | 0.362 |
| | 4 | -5.745 | 0.929 | -1.260 | -10.018 | 0.359 | 0.270 | 0.358 |
| | 4.5 | -5.808 | 0.936 | -1.272 | -10.069 | 0.360 | 0.260 | 0.359 |
| | 5 | -5.894 | 0.946 | -1.281 | -9.988 | 0.369 | 0.265 | 0.360 |

*Table 28. Coefficients for Interstorey Drift Ratio, α=8 (εσ is the total standard deviation)*

| | Period (s) | b1 | b2 | b3 | b4 | b5 | b6 | εσ |
|---|---|---|---|---|---|---|---|---|
| **z=0.05** | 0.1 | -2.572 | 0.588 | -2.050 | -14.006 | 0.285 | 0.219 | 0.398 |
| | 0.2 | -2.665 | 0.624 | -1.960 | -15.324 | 0.305 | 0.241 | 0.395 |
| | 0.3 | -3.183 | 0.655 | -1.759 | -13.344 | 0.310 | 0.263 | 0.367 |
| | 0.4 | -3.505 | 0.691 | -1.673 | -12.867 | 0.325 | 0.262 | 0.362 |
| | 0.5 | -3.773 | 0.722 | -1.614 | -12.725 | 0.336 | 0.251 | 0.367 |
| | 0.75 | -4.410 | 0.787 | -1.489 | -11.613 | 0.371 | 0.270 | 0.360 |
| | 1 | -4.817 | 0.826 | -1.419 | -10.364 | 0.399 | 0.292 | 0.361 |
| | 1.5 | -5.236 | 0.862 | -1.339 | -10.730 | 0.396 | 0.301 | 0.359 |
| | 2 | -5.544 | 0.894 | -1.308 | -9.875 | 0.387 | 0.282 | 0.360 |
| | 2.5 | -5.674 | 0.899 | -1.287 | -9.691 | 0.381 | 0.280 | 0.357 |
| | 3 | -5.746 | 0.898 | -1.280 | -10.041 | 0.399 | 0.286 | 0.357 |
| | 3.5 | -5.769 | 0.898 | -1.293 | -10.494 | 0.403 | 0.292 | 0.361 |
| | 4 | -5.848 | 0.900 | -1.279 | -10.037 | 0.386 | 0.286 | 0.359 |
| | 4.5 | -5.960 | 0.907 | -1.262 | -9.824 | 0.383 | 0.288 | 0.357 |
| | 5 | -6.103 | 0.926 | -1.261 | -9.630 | 0.377 | 0.280 | 0.354 |
| **z=0.10** | 0.1 | -2.346 | 0.587 | -2.055 | -14.036 | 0.284 | 0.218 | 0.399 |
| | 0.2 | -2.440 | 0.623 | -1.964 | -15.380 | 0.305 | 0.241 | 0.396 |
| | 0.3 | -2.968 | 0.656 | -1.760 | -13.374 | 0.309 | 0.263 | 0.368 |
| | 0.4 | -3.297 | 0.691 | -1.672 | -12.919 | 0.325 | 0.263 | 0.362 |
| | 0.5 | -3.575 | 0.724 | -1.611 | -12.754 | 0.335 | 0.251 | 0.367 |
| | 0.75 | -4.231 | 0.791 | -1.483 | -11.615 | 0.371 | 0.270 | 0.362 |
| | 1 | -4.650 | 0.831 | -1.414 | -10.460 | 0.399 | 0.294 | 0.364 |
| | 1.5 | -5.110 | 0.872 | -1.326 | -10.779 | 0.396 | 0.303 | 0.363 |
| | 2 | -5.468 | 0.910 | -1.290 | -9.957 | 0.385 | 0.284 | 0.366 |
| | 2.5 | -5.627 | 0.918 | -1.269 | -9.807 | 0.381 | 0.283 | 0.364 |
| | 3 | -5.735 | 0.921 | -1.256 | -10.154 | 0.398 | 0.288 | 0.366 |
| | 3.5 | -5.772 | 0.921 | -1.267 | -10.659 | 0.400 | 0.292 | 0.369 |
| | 4 | -5.872 | 0.926 | -1.252 | -10.168 | 0.386 | 0.285 | 0.368 |
| | 4.5 | -6.004 | 0.934 | -1.229 | -9.855 | 0.384 | 0.287 | 0.366 |
| | 5 | -6.155 | 0.953 | -1.227 | -9.682 | 0.376 | 0.280 | 0.364 |
| **z=0.20** | 0.1 | -2.175 | 0.584 | -2.068 | -14.125 | 0.282 | 0.217 | 0.401 |
| | 0.2 | -2.272 | 0.622 | -1.976 | -15.556 | 0.305 | 0.241 | 0.398 |
| | 0.3 | -2.834 | 0.657 | -1.762 | -13.476 | 0.308 | 0.264 | 0.370 |
| | 0.4 | -3.176 | 0.693 | -1.668 | -13.066 | 0.322 | 0.265 | 0.364 |
| | 0.5 | -3.490 | 0.729 | -1.601 | -12.787 | 0.334 | 0.254 | 0.369 |
| | 0.75 | -4.184 | 0.801 | -1.469 | -11.611 | 0.370 | 0.270 | 0.367 |
| | 1 | -4.618 | 0.843 | -1.402 | -10.681 | 0.401 | 0.299 | 0.369 |
| | 1.5 | -5.156 | 0.890 | -1.297 | -10.588 | 0.400 | 0.304 | 0.370 |
| | 2 | -5.536 | 0.932 | -1.265 | -10.232 | 0.382 | 0.289 | 0.371 |
| | 2.5 | -5.725 | 0.943 | -1.242 | -9.676 | 0.380 | 0.284 | 0.371 |
| | 3 | -5.855 | 0.949 | -1.228 | -10.068 | 0.400 | 0.290 | 0.374 |
| | 3.5 | -5.916 | 0.951 | -1.236 | -10.615 | 0.396 | 0.290 | 0.378 |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | 4 | -6.038 | 0.957 | -1.217 | -10.207 | 0.388 | 0.282 | 0.379 |
|  | 4.5 | -6.206 | 0.972 | -1.200 | -9.649 | 0.382 | 0.282 | 0.376 |
|  | 5 | -6.331 | 0.985 | -1.201 | -9.581 | 0.374 | 0.282 | 0.377 |
| **z=0.30** | 0.1 | -2.112 | 0.582 | -2.085 | -14.244 | 0.279 | 0.216 | 0.404 |
|  | 0.2 | -2.217 | 0.622 | -1.991 | -15.779 | 0.306 | 0.241 | 0.401 |
|  | 0.3 | -2.822 | 0.660 | -1.766 | -13.633 | 0.310 | 0.268 | 0.374 |
|  | 0.4 | -3.189 | 0.697 | -1.663 | -13.297 | 0.317 | 0.270 | 0.368 |
|  | 0.5 | -3.540 | 0.736 | -1.589 | -12.946 | 0.333 | 0.258 | 0.371 |
|  | 0.75 | -4.262 | 0.813 | -1.458 | -11.684 | 0.373 | 0.269 | 0.371 |
|  | 1 | -4.700 | 0.854 | -1.386 | -10.726 | 0.405 | 0.297 | 0.370 |
|  | 1.5 | -5.228 | 0.900 | -1.292 | -10.427 | 0.414 | 0.305 | 0.371 |
|  | 2 | -5.585 | 0.935 | -1.251 | -10.027 | 0.389 | 0.294 | 0.370 |
|  | 2.5 | -5.765 | 0.944 | -1.228 | -9.665 | 0.375 | 0.288 | 0.369 |
|  | 3 | -5.869 | 0.948 | -1.224 | -9.661 | 0.388 | 0.288 | 0.374 |
|  | 3.5 | -5.919 | 0.947 | -1.228 | -9.968 | 0.384 | 0.290 | 0.376 |
|  | 4 | -5.973 | 0.949 | -1.231 | -10.152 | 0.375 | 0.284 | 0.374 |
|  | 4.5 | -6.127 | 0.959 | -1.207 | -9.782 | 0.372 | 0.280 | 0.373 |
|  | 5 | -6.293 | 0.982 | -1.212 | -9.755 | 0.366 | 0.278 | 0.374 |
| **z=0.40** | 0.1 | -2.093 | 0.579 | -2.104 | -14.375 | 0.276 | 0.215 | 0.407 |
|  | 0.2 | -2.199 | 0.619 | -2.007 | -15.975 | 0.306 | 0.242 | 0.404 |
|  | 0.3 | -2.835 | 0.661 | -1.776 | -13.800 | 0.314 | 0.271 | 0.378 |
|  | 0.4 | -3.251 | 0.701 | -1.655 | -13.429 | 0.307 | 0.275 | 0.374 |
|  | 0.5 | -3.619 | 0.742 | -1.579 | -13.187 | 0.327 | 0.263 | 0.373 |
|  | 0.75 | -4.394 | 0.825 | -1.443 | -11.519 | 0.378 | 0.269 | 0.374 |
|  | 1 | -4.843 | 0.870 | -1.375 | -10.922 | 0.408 | 0.291 | 0.374 |
|  | 1.5 | -5.393 | 0.917 | -1.281 | -10.417 | 0.425 | 0.303 | 0.376 |
|  | 2 | -5.705 | 0.939 | -1.230 | -9.365 | 0.393 | 0.295 | 0.375 |
|  | 2.5 | -5.815 | 0.935 | -1.202 | -9.337 | 0.375 | 0.287 | 0.368 |
|  | 3 | -5.963 | 0.952 | -1.215 | -9.644 | 0.376 | 0.282 | 0.367 |
|  | 3.5 | -6.029 | 0.955 | -1.224 | -9.461 | 0.370 | 0.276 | 0.368 |
|  | 4 | -6.030 | 0.947 | -1.227 | -9.557 | 0.361 | 0.272 | 0.366 |
|  | 4.5 | -6.065 | 0.947 | -1.235 | -9.677 | 0.358 | 0.273 | 0.365 |
|  | 5 | -6.174 | 0.957 | -1.236 | -9.670 | 0.360 | 0.275 | 0.366 |
| **z=0.50** | 0.1 | -2.096 | 0.575 | -2.127 | -14.519 | 0.273 | 0.213 | 0.410 |
|  | 0.2 | -2.176 | 0.613 | -2.026 | -16.034 | 0.303 | 0.240 | 0.407 |
|  | 0.3 | -2.778 | 0.649 | -1.793 | -13.834 | 0.318 | 0.269 | 0.378 |
|  | 0.4 | -3.194 | 0.691 | -1.676 | -13.391 | 0.315 | 0.272 | 0.372 |
|  | 0.5 | -3.547 | 0.731 | -1.601 | -13.136 | 0.322 | 0.258 | 0.373 |
|  | 0.75 | -4.312 | 0.810 | -1.455 | -11.472 | 0.374 | 0.272 | 0.371 |
|  | 1 | -4.773 | 0.858 | -1.388 | -10.567 | 0.399 | 0.292 | 0.374 |
|  | 1.5 | -5.385 | 0.918 | -1.295 | -10.735 | 0.411 | 0.299 | 0.377 |
|  | 2 | -5.718 | 0.945 | -1.250 | -9.807 | 0.396 | 0.292 | 0.377 |
|  | 2.5 | -5.880 | 0.944 | -1.204 | -9.241 | 0.381 | 0.290 | 0.375 |
|  | 3 | -6.059 | 0.959 | -1.194 | -9.690 | 0.390 | 0.291 | 0.376 |

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|---|---|---|---|---|---|---|---|---|
|  | 3.5 | -6.154 | 0.969 | -1.209 | -10.315 | 0.379 | 0.283 | 0.375 |
|  | 4 | -6.236 | 0.974 | -1.208 | -10.139 | 0.362 | 0.268 | 0.375 |
|  | 4.5 | -6.370 | 0.989 | -1.214 | -9.884 | 0.359 | 0.267 | 0.376 |
|  | 5 | -6.443 | 0.995 | -1.223 | -10.084 | 0.354 | 0.271 | 0.377 |
| **z=0.60** | 0.1 | -2.114 | 0.571 | -2.157 | -14.656 | 0.269 | 0.212 | 0.415 |
|  | 0.2 | -2.138 | 0.602 | -2.055 | -16.094 | 0.297 | 0.235 | 0.409 |
|  | 0.3 | -2.663 | 0.629 | -1.827 | -13.862 | 0.315 | 0.262 | 0.377 |
|  | 0.4 | -3.025 | 0.670 | -1.729 | -13.533 | 0.318 | 0.264 | 0.368 |
|  | 0.5 | -3.331 | 0.706 | -1.662 | -13.186 | 0.322 | 0.252 | 0.370 |
|  | 0.75 | -4.017 | 0.772 | -1.508 | -11.643 | 0.361 | 0.272 | 0.363 |
|  | 1 | -4.455 | 0.818 | -1.440 | -10.822 | 0.382 | 0.291 | 0.364 |
|  | 1.5 | -5.023 | 0.876 | -1.346 | -10.802 | 0.399 | 0.294 | 0.366 |
|  | 2 | -5.377 | 0.910 | -1.303 | -10.007 | 0.391 | 0.286 | 0.370 |
|  | 2.5 | -5.574 | 0.922 | -1.272 | -9.863 | 0.392 | 0.291 | 0.371 |
|  | 3 | -5.731 | 0.929 | -1.248 | -9.867 | 0.411 | 0.299 | 0.374 |
|  | 3.5 | -5.809 | 0.936 | -1.254 | -10.155 | 0.400 | 0.297 | 0.374 |
|  | 4 | -5.929 | 0.943 | -1.237 | -10.057 | 0.385 | 0.288 | 0.371 |
|  | 4.5 | -6.050 | 0.953 | -1.225 | -9.937 | 0.377 | 0.284 | 0.371 |
|  | 5 | -6.207 | 0.973 | -1.227 | -10.046 | 0.362 | 0.283 | 0.370 |
| **z=0.70** | 0.1 | -2.143 | 0.565 | -2.198 | -14.817 | 0.263 | 0.210 | 0.421 |
|  | 0.2 | -2.098 | 0.589 | -2.096 | -16.136 | 0.289 | 0.229 | 0.414 |
|  | 0.3 | -2.545 | 0.610 | -1.876 | -14.009 | 0.308 | 0.253 | 0.379 |
|  | 0.4 | -2.853 | 0.648 | -1.790 | -13.746 | 0.313 | 0.254 | 0.369 |
|  | 0.5 | -3.100 | 0.680 | -1.736 | -13.562 | 0.320 | 0.245 | 0.372 |
|  | 0.75 | -3.739 | 0.741 | -1.583 | -12.234 | 0.353 | 0.270 | 0.362 |
|  | 1 | -4.199 | 0.785 | -1.488 | -10.978 | 0.360 | 0.287 | 0.364 |
|  | 1.5 | -4.764 | 0.843 | -1.386 | -11.177 | 0.381 | 0.292 | 0.368 |
|  | 2 | -5.173 | 0.887 | -1.335 | -10.411 | 0.390 | 0.285 | 0.371 |
|  | 2.5 | -5.450 | 0.916 | -1.311 | -10.430 | 0.398 | 0.290 | 0.374 |
|  | 3 | -5.657 | 0.930 | -1.277 | -10.307 | 0.414 | 0.300 | 0.382 |
|  | 3.5 | -5.766 | 0.938 | -1.269 | -10.837 | 0.406 | 0.304 | 0.384 |
|  | 4 | -5.940 | 0.953 | -1.248 | -10.638 | 0.402 | 0.301 | 0.382 |
|  | 4.5 | -6.118 | 0.965 | -1.216 | -9.812 | 0.395 | 0.294 | 0.383 |
|  | 5 | -6.292 | 0.987 | -1.214 | -9.830 | 0.376 | 0.290 | 0.382 |
| **z=0.80** | 0.1 | -2.155 | 0.556 | -2.269 | -15.095 | 0.254 | 0.208 | 0.433 |
|  | 0.2 | -2.048 | 0.574 | -2.159 | -16.323 | 0.277 | 0.223 | 0.422 |
|  | 0.3 | -2.434 | 0.592 | -1.947 | -14.333 | 0.299 | 0.245 | 0.386 |
|  | 0.4 | -2.699 | 0.626 | -1.863 | -14.046 | 0.307 | 0.245 | 0.375 |
|  | 0.5 | -2.888 | 0.654 | -1.816 | -14.027 | 0.317 | 0.239 | 0.378 |
|  | 0.75 | -3.470 | 0.709 | -1.664 | -12.920 | 0.346 | 0.265 | 0.361 |
|  | 1 | -3.939 | 0.751 | -1.549 | -11.192 | 0.346 | 0.279 | 0.364 |
|  | 1.5 | -4.508 | 0.811 | -1.440 | -11.740 | 0.361 | 0.292 | 0.368 |
|  | 2 | -5.005 | 0.868 | -1.374 | -10.798 | 0.372 | 0.286 | 0.377 |
|  | 2.5 | -5.289 | 0.895 | -1.335 | -10.610 | 0.390 | 0.288 | 0.377 |

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|---|---|---|---|---|---|---|---|---|
|  | 3 | -5.515 | 0.917 | -1.311 | -11.029 | 0.419 | 0.303 | 0.385 |
|  | 3.5 | -5.732 | 0.940 | -1.290 | -11.149 | 0.414 | 0.299 | 0.388 |
|  | 4 | -5.926 | 0.957 | -1.262 | -10.954 | 0.414 | 0.296 | 0.385 |
|  | 4.5 | -6.117 | 0.973 | -1.237 | -10.276 | 0.414 | 0.297 | 0.387 |
|  | 5 | -6.297 | 0.994 | -1.228 | -10.195 | 0.395 | 0.294 | 0.391 |
| **z=0.90** | 0.1 | -1.991 | 0.537 | -2.440 | -16.080 | 0.233 | 0.202 | 0.459 |
|  | 0.2 | -1.934 | 0.555 | -2.268 | -16.850 | 0.260 | 0.215 | 0.437 |
|  | 0.3 | -2.292 | 0.572 | -2.046 | -14.949 | 0.288 | 0.236 | 0.398 |
|  | 0.4 | -2.543 | 0.605 | -1.953 | -14.509 | 0.298 | 0.237 | 0.386 |
|  | 0.5 | -2.674 | 0.627 | -1.912 | -14.780 | 0.312 | 0.235 | 0.389 |
|  | 0.75 | -3.217 | 0.676 | -1.747 | -13.600 | 0.337 | 0.260 | 0.364 |
|  | 1 | -3.669 | 0.714 | -1.620 | -11.647 | 0.338 | 0.271 | 0.362 |
|  | 1.5 | -4.164 | 0.767 | -1.515 | -12.028 | 0.361 | 0.284 | 0.360 |
|  | 2 | -4.620 | 0.819 | -1.448 | -11.000 | 0.377 | 0.282 | 0.366 |
|  | 2.5 | -4.908 | 0.843 | -1.390 | -10.323 | 0.381 | 0.285 | 0.367 |
|  | 3 | -5.125 | 0.863 | -1.358 | -10.467 | 0.407 | 0.298 | 0.371 |
|  | 3.5 | -5.361 | 0.893 | -1.340 | -10.611 | 0.404 | 0.303 | 0.377 |
|  | 4 | -5.499 | 0.903 | -1.314 | -10.486 | 0.396 | 0.305 | 0.377 |
|  | 4.5 | -5.674 | 0.918 | -1.287 | -9.958 | 0.399 | 0.302 | 0.378 |
|  | 5 | -5.848 | 0.939 | -1.277 | -9.837 | 0.389 | 0.297 | 0.381 |
| **z=1.00** | 0.1 | -1.527 | 0.506 | -2.699 | -18.239 | 0.203 | 0.194 | 0.500 |
|  | 0.2 | -1.842 | 0.544 | -2.355 | -17.349 | 0.247 | 0.210 | 0.448 |
|  | 0.3 | -2.196 | 0.560 | -2.116 | -15.427 | 0.282 | 0.231 | 0.408 |
|  | 0.4 | -2.442 | 0.591 | -2.015 | -14.913 | 0.292 | 0.233 | 0.394 |
|  | 0.5 | -2.553 | 0.612 | -1.974 | -15.309 | 0.308 | 0.234 | 0.398 |
|  | 0.75 | -3.103 | 0.659 | -1.793 | -14.026 | 0.330 | 0.257 | 0.368 |
|  | 1 | -3.565 | 0.698 | -1.656 | -11.978 | 0.332 | 0.267 | 0.364 |
|  | 1.5 | -4.044 | 0.749 | -1.549 | -12.191 | 0.357 | 0.278 | 0.358 |
|  | 2 | -4.483 | 0.799 | -1.481 | -11.219 | 0.376 | 0.279 | 0.362 |
|  | 2.5 | -4.759 | 0.821 | -1.418 | -10.329 | 0.382 | 0.282 | 0.362 |
|  | 3 | -4.963 | 0.840 | -1.387 | -10.427 | 0.408 | 0.294 | 0.364 |
|  | 3.5 | -5.199 | 0.869 | -1.365 | -10.450 | 0.406 | 0.302 | 0.370 |
|  | 4 | -5.313 | 0.876 | -1.340 | -10.354 | 0.395 | 0.305 | 0.369 |
|  | 4.5 | -5.480 | 0.892 | -1.317 | -9.866 | 0.394 | 0.298 | 0.371 |
|  | 5 | -5.644 | 0.912 | -1.306 | -9.723 | 0.387 | 0.295 | 0.374 |

*Table 29. Coefficients for Interstorey Drift Ratio, α=30 (εσ is the total standard deviation)*

| | **Period (s)** | **b1** | **b2** | **b3** | **b4** | **b5** | **b6** | **εσ** |
|---|---|---|---|---|---|---|---|---|
| **z=0.05** | 0.1 | -2.225 | 0.587 | -2.054 | -14.042 | 0.284 | 0.219 | 0.399 |
| | 0.2 | -2.324 | 0.623 | -1.960 | -15.309 | 0.306 | 0.242 | 0.397 |
| | 0.3 | -2.861 | 0.654 | -1.749 | -13.242 | 0.317 | 0.265 | 0.371 |
| | 0.4 | -3.209 | 0.695 | -1.666 | -12.988 | 0.325 | 0.270 | 0.366 |
| | 0.5 | -3.503 | 0.726 | -1.595 | -12.854 | 0.328 | 0.258 | 0.369 |
| | 0.75 | -4.243 | 0.805 | -1.463 | -11.196 | 0.381 | 0.272 | 0.366 |
| | 1 | -4.573 | 0.833 | -1.403 | -10.608 | 0.405 | 0.299 | 0.361 |
| | 1.5 | -5.112 | 0.887 | -1.319 | -10.629 | 0.406 | 0.300 | 0.365 |
| | 2 | -5.397 | 0.913 | -1.289 | -9.732 | 0.391 | 0.286 | 0.365 |
| | 2.5 | -5.547 | 0.914 | -1.252 | -9.199 | 0.388 | 0.292 | 0.364 |
| | 3 | -5.602 | 0.913 | -1.250 | -9.844 | 0.388 | 0.288 | 0.367 |
| | 3.5 | -5.719 | 0.925 | -1.253 | -9.956 | 0.385 | 0.284 | 0.367 |
| | 4 | -5.827 | 0.935 | -1.250 | -9.614 | 0.378 | 0.287 | 0.367 |
| | 4.5 | -5.936 | 0.943 | -1.242 | -9.525 | 0.371 | 0.286 | 0.370 |
| | 5 | -5.966 | 0.944 | -1.253 | -9.806 | 0.366 | 0.282 | 0.366 |
| **z=0.10** | 0.1 | -2.132 | 0.586 | -2.060 | -14.078 | 0.283 | 0.218 | 0.400 |
| | 0.2 | -2.230 | 0.623 | -1.965 | -15.380 | 0.306 | 0.242 | 0.398 |
| | 0.3 | -2.776 | 0.654 | -1.751 | -13.283 | 0.316 | 0.266 | 0.371 |
| | 0.4 | -3.130 | 0.695 | -1.667 | -13.062 | 0.324 | 0.270 | 0.367 |
| | 0.5 | -3.435 | 0.728 | -1.593 | -12.880 | 0.328 | 0.259 | 0.370 |
| | 0.75 | -4.196 | 0.809 | -1.459 | -11.265 | 0.380 | 0.273 | 0.368 |
| | 1 | -4.555 | 0.841 | -1.397 | -10.682 | 0.403 | 0.299 | 0.366 |
| | 1.5 | -5.158 | 0.902 | -1.302 | -10.662 | 0.406 | 0.302 | 0.371 |
| | 2 | -5.483 | 0.933 | -1.269 | -9.815 | 0.386 | 0.284 | 0.372 |
| | 2.5 | -5.686 | 0.939 | -1.225 | -9.284 | 0.387 | 0.293 | 0.371 |
| | 3 | -5.748 | 0.938 | -1.223 | -10.035 | 0.390 | 0.289 | 0.375 |
| | 3.5 | -5.892 | 0.952 | -1.221 | -10.006 | 0.390 | 0.283 | 0.375 |
| | 4 | -6.011 | 0.962 | -1.218 | -9.697 | 0.382 | 0.283 | 0.373 |
| | 4.5 | -6.139 | 0.973 | -1.209 | -9.582 | 0.374 | 0.281 | 0.377 |
| | 5 | -6.203 | 0.978 | -1.216 | -9.761 | 0.368 | 0.277 | 0.373 |
| **z=0.20** | 0.1 | -2.092 | 0.583 | -2.081 | -14.219 | 0.280 | 0.216 | 0.403 |
| | 0.2 | -2.187 | 0.620 | -1.985 | -15.640 | 0.305 | 0.242 | 0.401 |
| | 0.3 | -2.765 | 0.654 | -1.759 | -13.456 | 0.314 | 0.267 | 0.373 |
| | 0.4 | -3.134 | 0.695 | -1.668 | -13.228 | 0.321 | 0.271 | 0.369 |
| | 0.5 | -3.471 | 0.731 | -1.589 | -12.827 | 0.331 | 0.260 | 0.371 |
| | 0.75 | -4.221 | 0.811 | -1.456 | -11.433 | 0.377 | 0.269 | 0.370 |
| | 1 | -4.620 | 0.848 | -1.389 | -10.697 | 0.404 | 0.296 | 0.368 |
| | 1.5 | -5.200 | 0.904 | -1.296 | -10.646 | 0.413 | 0.303 | 0.371 |
| | 2 | -5.533 | 0.936 | -1.262 | -9.831 | 0.387 | 0.292 | 0.376 |
| | 2.5 | -5.759 | 0.947 | -1.220 | -9.335 | 0.383 | 0.293 | 0.373 |
| | 3 | -5.838 | 0.949 | -1.222 | -10.055 | 0.384 | 0.290 | 0.380 |
| | 3.5 | -5.951 | 0.956 | -1.216 | -10.021 | 0.383 | 0.289 | 0.381 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 4 | -6.082 | 0.968 | -1.211 | -9.711 | 0.375 | 0.286 | 0.380 |
| | 4.5 | -6.205 | 0.979 | -1.209 | -9.567 | 0.369 | 0.284 | 0.382 |
| | 5 | -6.284 | 0.987 | -1.214 | -9.903 | 0.362 | 0.280 | 0.378 |
| **z=0.30** | 0.1 | -2.082 | 0.579 | -2.104 | -14.372 | 0.276 | 0.215 | 0.407 |
| | 0.2 | -2.178 | 0.618 | -2.007 | -15.942 | 0.305 | 0.242 | 0.404 |
| | 0.3 | -2.789 | 0.655 | -1.772 | -13.681 | 0.313 | 0.269 | 0.376 |
| | 0.4 | -3.183 | 0.696 | -1.666 | -13.364 | 0.314 | 0.272 | 0.371 |
| | 0.5 | -3.523 | 0.732 | -1.588 | -12.946 | 0.330 | 0.259 | 0.371 |
| | 0.75 | -4.248 | 0.810 | -1.460 | -11.474 | 0.378 | 0.268 | 0.368 |
| | 1 | -4.672 | 0.850 | -1.391 | -10.666 | 0.410 | 0.296 | 0.367 |
| | 1.5 | -5.212 | 0.900 | -1.302 | -10.398 | 0.411 | 0.307 | 0.374 |
| | 2 | -5.575 | 0.933 | -1.254 | -9.764 | 0.385 | 0.296 | 0.377 |
| | 2.5 | -5.727 | 0.934 | -1.220 | -9.349 | 0.367 | 0.297 | 0.376 |
| | 3 | -5.876 | 0.950 | -1.222 | -10.051 | 0.373 | 0.284 | 0.378 |
| | 3.5 | -5.993 | 0.962 | -1.231 | -10.386 | 0.382 | 0.287 | 0.379 |
| | 4 | -6.075 | 0.967 | -1.231 | -10.476 | 0.370 | 0.278 | 0.379 |
| | 4.5 | -6.219 | 0.983 | -1.231 | -10.522 | 0.367 | 0.276 | 0.383 |
| | 5 | -6.321 | 0.994 | -1.236 | -10.700 | 0.366 | 0.274 | 0.382 |
| **z=0.40** | 0.1 | -2.098 | 0.576 | -2.123 | -14.483 | 0.273 | 0.213 | 0.410 |
| | 0.2 | -2.186 | 0.614 | -2.023 | -16.056 | 0.304 | 0.241 | 0.407 |
| | 0.3 | -2.803 | 0.653 | -1.789 | -13.777 | 0.314 | 0.268 | 0.378 |
| | 0.4 | -3.213 | 0.693 | -1.670 | -13.373 | 0.308 | 0.274 | 0.372 |
| | 0.5 | -3.548 | 0.727 | -1.592 | -13.007 | 0.327 | 0.261 | 0.370 |
| | 0.75 | -4.314 | 0.812 | -1.457 | -11.179 | 0.376 | 0.266 | 0.370 |
| | 1 | -4.715 | 0.850 | -1.393 | -10.725 | 0.410 | 0.293 | 0.367 |
| | 1.5 | -5.216 | 0.896 | -1.314 | -10.151 | 0.417 | 0.299 | 0.371 |
| | 2 | -5.523 | 0.919 | -1.264 | -9.577 | 0.388 | 0.288 | 0.368 |
| | 2.5 | -5.693 | 0.926 | -1.236 | -9.402 | 0.370 | 0.293 | 0.372 |
| | 3 | -5.795 | 0.934 | -1.240 | -9.608 | 0.371 | 0.287 | 0.371 |
| | 3.5 | -5.892 | 0.945 | -1.250 | -9.790 | 0.369 | 0.279 | 0.369 |
| | 4 | -5.985 | 0.950 | -1.246 | -9.860 | 0.364 | 0.285 | 0.375 |
| | 4.5 | -6.074 | 0.959 | -1.251 | -9.937 | 0.351 | 0.278 | 0.374 |
| | 5 | -6.102 | 0.957 | -1.253 | -10.321 | 0.357 | 0.280 | 0.373 |
| **z=0.50** | 0.1 | -2.127 | 0.571 | -2.148 | -14.575 | 0.269 | 0.211 | 0.414 |
| | 0.2 | -2.177 | 0.606 | -2.046 | -16.043 | 0.299 | 0.239 | 0.409 |
| | 0.3 | -2.722 | 0.638 | -1.820 | -13.909 | 0.317 | 0.262 | 0.378 |
| | 0.4 | -3.107 | 0.677 | -1.709 | -13.354 | 0.316 | 0.269 | 0.371 |
| | 0.5 | -3.389 | 0.707 | -1.639 | -13.262 | 0.319 | 0.259 | 0.368 |
| | 0.75 | -4.161 | 0.790 | -1.496 | -11.293 | 0.370 | 0.264 | 0.365 |
| | 1 | -4.573 | 0.829 | -1.421 | -10.532 | 0.392 | 0.295 | 0.366 |
| | 1.5 | -5.174 | 0.892 | -1.335 | -10.586 | 0.405 | 0.299 | 0.372 |
| | 2 | -5.514 | 0.920 | -1.283 | -9.876 | 0.393 | 0.296 | 0.376 |
| | 2.5 | -5.815 | 0.945 | -1.237 | -9.770 | 0.380 | 0.294 | 0.377 |
| | 3 | -5.960 | 0.956 | -1.229 | -10.317 | 0.383 | 0.291 | 0.381 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3.5 | -6.085 | 0.968 | -1.230 | -10.418 | 0.378 | 0.287 | 0.383 |
| | 4 | -6.231 | 0.979 | -1.217 | -10.217 | 0.378 | 0.282 | 0.385 |
| | 4.5 | -6.394 | 0.998 | -1.215 | -10.401 | 0.371 | 0.281 | 0.386 |
| | 5 | -6.469 | 1.002 | -1.215 | -10.984 | 0.375 | 0.280 | 0.387 |
| **z=0.60** | 0.1 | -2.167 | 0.566 | -2.185 | -14.694 | 0.264 | 0.208 | 0.420 |
| | 0.2 | -2.147 | 0.593 | -2.086 | -16.103 | 0.290 | 0.234 | 0.413 |
| | 0.3 | -2.601 | 0.617 | -1.872 | -14.042 | 0.314 | 0.254 | 0.379 |
| | 0.4 | -2.943 | 0.654 | -1.771 | -13.462 | 0.319 | 0.260 | 0.372 |
| | 0.5 | -3.180 | 0.684 | -1.716 | -13.698 | 0.315 | 0.253 | 0.367 |
| | 0.75 | -3.861 | 0.748 | -1.554 | -11.661 | 0.362 | 0.268 | 0.358 |
| | 1 | -4.243 | 0.788 | -1.486 | -10.923 | 0.376 | 0.290 | 0.357 |
| | 1.5 | -4.800 | 0.849 | -1.402 | -11.018 | 0.393 | 0.293 | 0.362 |
| | 2 | -5.179 | 0.885 | -1.344 | -9.862 | 0.390 | 0.289 | 0.368 |
| | 2.5 | -5.384 | 0.896 | -1.302 | -9.760 | 0.385 | 0.299 | 0.371 |
| | 3 | -5.543 | 0.906 | -1.277 | -10.056 | 0.393 | 0.302 | 0.374 |
| | 3.5 | -5.745 | 0.930 | -1.264 | -10.194 | 0.383 | 0.294 | 0.374 |
| | 4 | -5.893 | 0.946 | -1.259 | -10.063 | 0.377 | 0.291 | 0.379 |
| | 4.5 | -6.010 | 0.959 | -1.258 | -10.091 | 0.368 | 0.287 | 0.381 |
| | 5 | -6.111 | 0.967 | -1.252 | -10.222 | 0.370 | 0.282 | 0.378 |
| **z=0.70** | 0.1 | -2.233 | 0.559 | -2.247 | -14.867 | 0.256 | 0.206 | 0.431 |
| | 0.2 | -2.100 | 0.576 | -2.153 | -16.296 | 0.277 | 0.226 | 0.420 |
| | 0.3 | -2.469 | 0.592 | -1.944 | -14.271 | 0.306 | 0.246 | 0.386 |
| | 0.4 | -2.767 | 0.631 | -1.860 | -13.955 | 0.316 | 0.253 | 0.381 |
| | 0.5 | -2.958 | 0.655 | -1.803 | -14.300 | 0.314 | 0.246 | 0.374 |
| | 0.75 | -3.663 | 0.719 | -1.620 | -12.129 | 0.346 | 0.268 | 0.360 |
| | 1 | -4.062 | 0.756 | -1.528 | -11.355 | 0.347 | 0.287 | 0.361 |
| | 1.5 | -4.691 | 0.831 | -1.437 | -11.272 | 0.375 | 0.292 | 0.367 |
| | 2 | -5.132 | 0.877 | -1.370 | -10.604 | 0.380 | 0.284 | 0.375 |
| | 2.5 | -5.413 | 0.900 | -1.325 | -10.339 | 0.398 | 0.298 | 0.379 |
| | 3 | -5.614 | 0.920 | -1.306 | -10.894 | 0.403 | 0.305 | 0.385 |
| | 3.5 | -5.848 | 0.941 | -1.269 | -10.606 | 0.406 | 0.305 | 0.385 |
| | 4 | -6.060 | 0.960 | -1.240 | -9.977 | 0.400 | 0.304 | 0.388 |
| | 4.5 | -6.204 | 0.978 | -1.243 | -10.289 | 0.390 | 0.296 | 0.385 |
| | 5 | -6.313 | 0.986 | -1.232 | -10.566 | 0.382 | 0.291 | 0.385 |
| **z=0.80** | 0.1 | -1.632 | 0.510 | -2.676 | -17.803 | 0.206 | 0.192 | 0.501 |
| | 0.2 | -1.811 | 0.540 | -2.375 | -17.580 | 0.243 | 0.210 | 0.450 |
| | 0.3 | -2.148 | 0.550 | -2.130 | -15.447 | 0.288 | 0.230 | 0.410 |
| | 0.4 | -2.427 | 0.591 | -2.037 | -15.176 | 0.304 | 0.243 | 0.404 |
| | 0.5 | -2.577 | 0.609 | -1.970 | -15.647 | 0.311 | 0.237 | 0.396 |
| | 0.75 | -3.245 | 0.664 | -1.756 | -13.276 | 0.328 | 0.258 | 0.370 |
| | 1 | -3.624 | 0.698 | -1.647 | -12.478 | 0.328 | 0.275 | 0.366 |
| | 1.5 | -4.274 | 0.774 | -1.532 | -12.324 | 0.361 | 0.289 | 0.364 |
| | 2 | -4.798 | 0.829 | -1.438 | -10.948 | 0.370 | 0.276 | 0.373 |
| | 2.5 | -5.126 | 0.861 | -1.387 | -10.815 | 0.385 | 0.298 | 0.377 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3 | -5.380 | 0.887 | -1.351 | -11.017 | 0.397 | 0.302 | 0.382 |
| | 3.5 | -5.643 | 0.916 | -1.318 | -11.061 | 0.403 | 0.304 | 0.386 |
| | 4 | -5.848 | 0.931 | -1.281 | -10.365 | 0.403 | 0.312 | 0.388 |
| | 4.5 | -6.035 | 0.952 | -1.264 | -10.234 | 0.394 | 0.301 | 0.390 |
| | 5 | -6.182 | 0.967 | -1.249 | -10.498 | 0.389 | 0.302 | 0.387 |
| **z=0.90** | 0.1 | -3.421 | 0.600 | -1.948 | -12.515 | 0.309 | 0.227 | 0.382 |
| | 0.2 | -2.997 | 0.587 | -1.976 | -13.325 | 0.272 | 0.219 | 0.386 |
| | 0.3 | -2.845 | 0.586 | -1.974 | -13.317 | 0.307 | 0.234 | 0.386 |
| | 0.4 | -2.807 | 0.605 | -1.987 | -14.175 | 0.318 | 0.240 | 0.395 |
| | 0.5 | -2.903 | 0.623 | -1.945 | -14.467 | 0.315 | 0.231 | 0.392 |
| | 0.75 | -3.208 | 0.641 | -1.798 | -13.008 | 0.330 | 0.254 | 0.371 |
| | 1 | -3.427 | 0.662 | -1.720 | -12.781 | 0.325 | 0.261 | 0.364 |
| | 1.5 | -3.890 | 0.719 | -1.633 | -12.714 | 0.346 | 0.272 | 0.361 |
| | 2 | -4.342 | 0.766 | -1.541 | -11.511 | 0.354 | 0.273 | 0.366 |
| | 2.5 | -4.651 | 0.791 | -1.468 | -10.940 | 0.362 | 0.292 | 0.368 |
| | 3 | -4.909 | 0.817 | -1.418 | -11.145 | 0.374 | 0.296 | 0.373 |
| | 3.5 | -5.206 | 0.855 | -1.392 | -11.067 | 0.383 | 0.301 | 0.378 |
| | 4 | -5.445 | 0.880 | -1.355 | -10.383 | 0.378 | 0.300 | 0.382 |
| | 4.5 | -5.630 | 0.901 | -1.335 | -10.283 | 0.383 | 0.293 | 0.384 |
| | 5 | -5.740 | 0.908 | -1.314 | -10.350 | 0.386 | 0.297 | 0.384 |
| **z=1.00** | 0.1 | -2.875 | 0.589 | -2.046 | -13.937 | 0.287 | 0.220 | 0.397 |
| | 0.2 | -2.910 | 0.618 | -1.962 | -15.074 | 0.302 | 0.239 | 0.394 |
| | 0.3 | -3.311 | 0.636 | -1.777 | -12.970 | 0.317 | 0.257 | 0.366 |
| | 0.4 | -3.553 | 0.668 | -1.716 | -12.594 | 0.322 | 0.256 | 0.362 |
| | 0.5 | -3.704 | 0.685 | -1.668 | -12.836 | 0.331 | 0.246 | 0.362 |
| | 0.75 | -4.213 | 0.738 | -1.562 | -11.146 | 0.380 | 0.259 | 0.352 |
| | 1 | -4.360 | 0.748 | -1.517 | -10.745 | 0.376 | 0.277 | 0.347 |
| | 1.5 | -4.663 | 0.783 | -1.471 | -10.968 | 0.382 | 0.289 | 0.351 |
| | 2 | -4.911 | 0.811 | -1.442 | -10.071 | 0.365 | 0.283 | 0.356 |
| | 2.5 | -5.063 | 0.816 | -1.396 | -9.889 | 0.369 | 0.291 | 0.356 |
| | 3 | -5.131 | 0.820 | -1.389 | -10.624 | 0.369 | 0.294 | 0.364 |
| | 3.5 | -5.335 | 0.848 | -1.384 | -10.727 | 0.374 | 0.300 | 0.367 |
| | 4 | -5.475 | 0.863 | -1.369 | -10.427 | 0.362 | 0.292 | 0.371 |
| | 4.5 | -5.665 | 0.884 | -1.345 | -10.128 | 0.365 | 0.289 | 0.373 |
| | 5 | -5.762 | 0.893 | -1.335 | -10.247 | 0.366 | 0.288 | 0.373 |

Table 30, Table 31, and Table 32 display the coefficients computed for PFA. 10 values of *z* have been selected for illustrative purposes.

*Table 30. Coefficients for Peak-Floor Acceleration, α=0.1 (εσ is the total standard deviation)*

| | **Period (s)** | **b1** | **b2** | **b3** | **b4** | **b5** | **b6** | **εσ** |
|---|---|---|---|---|---|---|---|---|
| **z=0.05** | 0.1 | -1.371 | 0.620 | -1.840 | -12.229 | 0.317 | 0.235 | 0.370 |
| | 0.2 | -1.373 | 0.620 | -1.838 | -12.218 | 0.317 | 0.235 | 0.370 |
| | 0.3 | -1.371 | 0.620 | -1.839 | -12.209 | 0.316 | 0.235 | 0.370 |
| | 0.4 | -1.370 | 0.620 | -1.840 | -12.226 | 0.318 | 0.234 | 0.370 |
| | 0.5 | -1.368 | 0.620 | -1.841 | -12.266 | 0.318 | 0.235 | 0.370 |
| | 0.75 | -1.371 | 0.620 | -1.841 | -12.244 | 0.317 | 0.235 | 0.370 |
| | 1 | -1.367 | 0.620 | -1.841 | -12.255 | 0.317 | 0.234 | 0.370 |
| | 1.5 | -1.365 | 0.619 | -1.840 | -12.309 | 0.317 | 0.236 | 0.370 |
| | 2 | -1.385 | 0.621 | -1.838 | -12.196 | 0.318 | 0.235 | 0.370 |
| | 2.5 | -1.375 | 0.621 | -1.840 | -12.356 | 0.319 | 0.236 | 0.370 |
| | 3 | -1.374 | 0.620 | -1.839 | -12.373 | 0.318 | 0.235 | 0.369 |
| | 3.5 | -1.397 | 0.621 | -1.831 | -12.258 | 0.318 | 0.235 | 0.369 |
| | 4 | -1.403 | 0.622 | -1.832 | -12.323 | 0.319 | 0.237 | 0.369 |
| | 4.5 | -1.407 | 0.623 | -1.835 | -12.365 | 0.320 | 0.238 | 0.369 |
| | 5 | -1.425 | 0.624 | -1.828 | -12.263 | 0.321 | 0.238 | 0.369 |
| **z=0.10** | 0.1 | -1.353 | 0.619 | -1.844 | -12.193 | 0.317 | 0.234 | 0.371 |
| | 0.2 | -1.364 | 0.619 | -1.838 | -12.140 | 0.315 | 0.234 | 0.369 |
| | 0.3 | -1.355 | 0.618 | -1.840 | -12.091 | 0.314 | 0.234 | 0.369 |
| | 0.4 | -1.347 | 0.618 | -1.844 | -12.141 | 0.316 | 0.230 | 0.369 |
| | 0.5 | -1.335 | 0.618 | -1.849 | -12.319 | 0.317 | 0.234 | 0.371 |
| | 0.75 | -1.344 | 0.619 | -1.849 | -12.196 | 0.318 | 0.235 | 0.372 |
| | 1 | -1.326 | 0.618 | -1.851 | -12.260 | 0.314 | 0.235 | 0.372 |
| | 1.5 | -1.327 | 0.616 | -1.847 | -12.365 | 0.313 | 0.237 | 0.369 |
| | 2 | -1.375 | 0.623 | -1.842 | -12.046 | 0.315 | 0.234 | 0.371 |
| | 2.5 | -1.347 | 0.621 | -1.850 | -12.425 | 0.319 | 0.238 | 0.370 |
| | 3 | -1.318 | 0.620 | -1.859 | -12.690 | 0.315 | 0.234 | 0.370 |
| | 3.5 | -1.362 | 0.622 | -1.845 | -12.518 | 0.313 | 0.235 | 0.367 |
| | 4 | -1.380 | 0.620 | -1.832 | -12.353 | 0.318 | 0.239 | 0.369 |
| | 4.5 | -1.375 | 0.620 | -1.836 | -12.415 | 0.313 | 0.241 | 0.368 |
| | 5 | -1.431 | 0.628 | -1.833 | -12.184 | 0.319 | 0.240 | 0.369 |
| **z=0.20** | 0.1 | -1.307 | 0.617 | -1.854 | -12.218 | 0.318 | 0.233 | 0.372 |
| | 0.2 | -1.351 | 0.618 | -1.836 | -12.113 | 0.311 | 0.234 | 0.368 |
| | 0.3 | -1.339 | 0.615 | -1.836 | -11.752 | 0.308 | 0.231 | 0.368 |
| | 0.4 | -1.273 | 0.612 | -1.855 | -11.901 | 0.305 | 0.220 | 0.369 |
| | 0.5 | -1.226 | 0.612 | -1.877 | -12.389 | 0.307 | 0.226 | 0.372 |
| | 0.75 | -1.191 | 0.610 | -1.881 | -12.315 | 0.321 | 0.238 | 0.378 |
| | 1 | -1.173 | 0.616 | -1.899 | -12.508 | 0.307 | 0.237 | 0.382 |
| | 1.5 | -1.152 | 0.604 | -1.873 | -12.843 | 0.296 | 0.234 | 0.371 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2 | -1.235 | 0.616 | -1.863 | -12.236 | 0.310 | 0.239 | 0.372 |
| | 2.5 | -1.207 | 0.620 | -1.882 | -12.818 | 0.316 | 0.233 | 0.371 |
| | 3 | -1.210 | 0.622 | -1.883 | -13.224 | 0.312 | 0.231 | 0.378 |
| | 3.5 | -1.298 | 0.632 | -1.864 | -13.199 | 0.311 | 0.240 | 0.372 |
| | 4 | -1.296 | 0.622 | -1.841 | -12.947 | 0.318 | 0.243 | 0.368 |
| | 4.5 | -1.356 | 0.627 | -1.830 | -12.774 | 0.317 | 0.245 | 0.363 |
| | 5 | -1.435 | 0.636 | -1.820 | -12.576 | 0.320 | 0.247 | 0.364 |
| **z=0.30** | 0.1 | -1.224 | 0.616 | -1.881 | -12.573 | 0.316 | 0.233 | 0.375 |
| | 0.2 | -1.307 | 0.620 | -1.846 | -12.519 | 0.306 | 0.236 | 0.369 |
| | 0.3 | -1.352 | 0.616 | -1.820 | -11.461 | 0.303 | 0.228 | 0.367 |
| | 0.4 | -1.223 | 0.609 | -1.854 | -11.764 | 0.291 | 0.211 | 0.369 |
| | 0.5 | -1.148 | 0.608 | -1.884 | -12.190 | 0.295 | 0.218 | 0.373 |
| | 0.75 | -1.034 | 0.606 | -1.923 | -12.648 | 0.323 | 0.240 | 0.385 |
| | 1 | -1.044 | 0.619 | -1.945 | -13.051 | 0.315 | 0.244 | 0.393 |
| | 1.5 | -1.057 | 0.604 | -1.881 | -13.519 | 0.285 | 0.239 | 0.372 |
| | 2 | -1.219 | 0.617 | -1.844 | -12.664 | 0.309 | 0.245 | 0.368 |
| | 2.5 | -1.291 | 0.630 | -1.841 | -12.888 | 0.316 | 0.239 | 0.367 |
| | 3 | -1.320 | 0.636 | -1.842 | -13.243 | 0.324 | 0.231 | 0.378 |
| | 3.5 | -1.502 | 0.652 | -1.799 | -12.881 | 0.326 | 0.243 | 0.373 |
| | 4 | -1.554 | 0.652 | -1.778 | -12.921 | 0.328 | 0.244 | 0.363 |
| | 4.5 | -1.621 | 0.655 | -1.763 | -12.825 | 0.331 | 0.250 | 0.357 |
| | 5 | -1.710 | 0.655 | -1.731 | -12.175 | 0.340 | 0.256 | 0.355 |
| **z=0.40** | 0.1 | -1.058 | 0.610 | -1.927 | -13.062 | 0.309 | 0.231 | 0.380 |
| | 0.2 | -1.215 | 0.621 | -1.866 | -13.093 | 0.306 | 0.239 | 0.374 |
| | 0.3 | -1.341 | 0.618 | -1.806 | -11.512 | 0.298 | 0.229 | 0.365 |
| | 0.4 | -1.252 | 0.614 | -1.828 | -11.516 | 0.280 | 0.207 | 0.368 |
| | 0.5 | -1.147 | 0.610 | -1.866 | -12.058 | 0.289 | 0.211 | 0.371 |
| | 0.75 | -1.032 | 0.613 | -1.920 | -12.632 | 0.329 | 0.239 | 0.386 |
| | 1 | -1.049 | 0.625 | -1.934 | -13.231 | 0.329 | 0.251 | 0.397 |
| | 1.5 | -1.170 | 0.621 | -1.854 | -13.639 | 0.298 | 0.251 | 0.375 |
| | 2 | -1.394 | 0.630 | -1.780 | -12.338 | 0.303 | 0.247 | 0.364 |
| | 2.5 | -1.471 | 0.644 | -1.785 | -12.748 | 0.310 | 0.240 | 0.358 |
| | 3 | -1.515 | 0.649 | -1.783 | -12.886 | 0.320 | 0.234 | 0.363 |
| | 3.5 | -1.639 | 0.659 | -1.755 | -12.660 | 0.337 | 0.246 | 0.363 |
| | 4 | -1.751 | 0.670 | -1.736 | -12.311 | 0.334 | 0.237 | 0.356 |
| | 4.5 | -1.837 | 0.676 | -1.720 | -12.245 | 0.339 | 0.243 | 0.354 |
| | 5 | -1.853 | 0.673 | -1.712 | -12.046 | 0.343 | 0.245 | 0.353 |
| **z=0.50** | 0.1 | -0.842 | 0.600 | -1.983 | -13.520 | 0.298 | 0.225 | 0.388 |
| | 0.2 | -1.080 | 0.623 | -1.901 | -13.866 | 0.308 | 0.240 | 0.383 |
| | 0.3 | -1.356 | 0.627 | -1.791 | -11.814 | 0.296 | 0.235 | 0.364 |
| | 0.4 | -1.352 | 0.627 | -1.786 | -11.385 | 0.275 | 0.212 | 0.364 |
| | 0.5 | -1.270 | 0.621 | -1.811 | -11.913 | 0.286 | 0.210 | 0.363 |
| | 0.75 | -1.194 | 0.626 | -1.861 | -12.188 | 0.339 | 0.239 | 0.380 |
| | 1 | -1.202 | 0.637 | -1.882 | -12.906 | 0.342 | 0.256 | 0.393 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1.5 | -1.380 | 0.643 | -1.811 | -13.446 | 0.323 | 0.265 | 0.377 |
| | 2 | -1.598 | 0.649 | -1.740 | -12.156 | 0.303 | 0.253 | 0.366 |
| | 2.5 | -1.679 | 0.652 | -1.715 | -12.103 | 0.295 | 0.247 | 0.358 |
| | 3 | -1.696 | 0.650 | -1.709 | -12.464 | 0.298 | 0.234 | 0.353 |
| | 3.5 | -1.795 | 0.662 | -1.705 | -12.246 | 0.325 | 0.241 | 0.352 |
| | 4 | -1.867 | 0.674 | -1.712 | -12.082 | 0.353 | 0.245 | 0.348 |
| | 4.5 | -1.943 | 0.683 | -1.709 | -11.634 | 0.358 | 0.246 | 0.350 |
| | 5 | -1.969 | 0.688 | -1.716 | -11.479 | 0.349 | 0.243 | 0.354 |
| **z=0.60** | 0.1 | -0.630 | 0.590 | -2.036 | -13.912 | 0.287 | 0.220 | 0.396 |
| | 0.2 | -0.928 | 0.624 | -1.942 | -14.728 | 0.310 | 0.240 | 0.392 |
| | 0.3 | -1.390 | 0.640 | -1.777 | -12.429 | 0.301 | 0.249 | 0.366 |
| | 0.4 | -1.527 | 0.648 | -1.732 | -11.517 | 0.280 | 0.226 | 0.359 |
| | 0.5 | -1.552 | 0.648 | -1.728 | -11.674 | 0.293 | 0.215 | 0.356 |
| | 0.75 | -1.536 | 0.652 | -1.764 | -11.418 | 0.358 | 0.241 | 0.366 |
| | 1 | -1.496 | 0.657 | -1.800 | -11.794 | 0.348 | 0.256 | 0.380 |
| | 1.5 | -1.476 | 0.646 | -1.782 | -12.628 | 0.322 | 0.258 | 0.372 |
| | 2 | -1.529 | 0.638 | -1.752 | -11.896 | 0.325 | 0.259 | 0.367 |
| | 2.5 | -1.584 | 0.647 | -1.752 | -12.229 | 0.310 | 0.249 | 0.362 |
| | 3 | -1.557 | 0.645 | -1.765 | -12.753 | 0.311 | 0.241 | 0.365 |
| | 3.5 | -1.614 | 0.650 | -1.760 | -12.804 | 0.312 | 0.244 | 0.365 |
| | 4 | -1.727 | 0.657 | -1.734 | -12.454 | 0.327 | 0.242 | 0.350 |
| | 4.5 | -1.805 | 0.663 | -1.721 | -12.042 | 0.328 | 0.243 | 0.351 |
| | 5 | -1.880 | 0.672 | -1.718 | -11.836 | 0.333 | 0.244 | 0.349 |
| **z=0.70** | 0.1 | -0.432 | 0.581 | -2.087 | -14.271 | 0.279 | 0.216 | 0.404 |
| | 0.2 | -0.745 | 0.621 | -1.988 | -15.596 | 0.308 | 0.242 | 0.401 |
| | 0.3 | -1.397 | 0.653 | -1.779 | -13.380 | 0.309 | 0.264 | 0.374 |
| | 0.4 | -1.749 | 0.676 | -1.676 | -12.246 | 0.290 | 0.252 | 0.363 |
| | 0.5 | -1.957 | 0.692 | -1.634 | -11.884 | 0.307 | 0.235 | 0.358 |
| | 0.75 | -2.175 | 0.709 | -1.615 | -10.388 | 0.375 | 0.245 | 0.347 |
| | 1 | -2.105 | 0.703 | -1.657 | -10.176 | 0.367 | 0.255 | 0.357 |
| | 1.5 | -1.885 | 0.673 | -1.698 | -10.897 | 0.324 | 0.248 | 0.367 |
| | 2 | -1.640 | 0.643 | -1.750 | -11.002 | 0.324 | 0.251 | 0.374 |
| | 2.5 | -1.538 | 0.643 | -1.800 | -11.828 | 0.311 | 0.241 | 0.375 |
| | 3 | -1.393 | 0.630 | -1.837 | -12.830 | 0.322 | 0.240 | 0.381 |
| | 3.5 | -1.355 | 0.631 | -1.859 | -13.602 | 0.318 | 0.242 | 0.381 |
| | 4 | -1.371 | 0.629 | -1.851 | -13.732 | 0.321 | 0.240 | 0.371 |
| | 4.5 | -1.486 | 0.640 | -1.835 | -13.317 | 0.319 | 0.243 | 0.366 |
| | 5 | -1.548 | 0.638 | -1.806 | -12.841 | 0.325 | 0.249 | 0.365 |
| **z=0.80** | 0.1 | -0.256 | 0.575 | -2.133 | -14.565 | 0.272 | 0.213 | 0.411 |
| | 0.2 | -0.547 | 0.614 | -2.031 | -16.153 | 0.303 | 0.241 | 0.408 |
| | 0.3 | -1.284 | 0.652 | -1.793 | -13.847 | 0.314 | 0.269 | 0.378 |
| | 0.4 | -1.761 | 0.689 | -1.674 | -13.299 | 0.307 | 0.269 | 0.372 |
| | 0.5 | -2.140 | 0.723 | -1.602 | -12.881 | 0.323 | 0.255 | 0.367 |
| | 0.75 | -2.812 | 0.780 | -1.492 | -10.718 | 0.379 | 0.257 | 0.356 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | -3.003 | 0.790 | -1.479 | -9.461 | 0.383 | 0.259 | 0.349 |
| | 1.5 | -2.914 | 0.765 | -1.506 | -8.726 | 0.363 | 0.248 | 0.358 |
| | 2 | -2.449 | 0.715 | -1.629 | -8.936 | 0.336 | 0.240 | 0.369 |
| | 2.5 | -2.059 | 0.679 | -1.726 | -9.644 | 0.306 | 0.225 | 0.380 |
| | 3 | -1.727 | 0.648 | -1.804 | -10.908 | 0.312 | 0.230 | 0.397 |
| | 3.5 | -1.519 | 0.637 | -1.871 | -11.918 | 0.301 | 0.227 | 0.396 |
| | 4 | -1.268 | 0.606 | -1.913 | -12.677 | 0.296 | 0.229 | 0.391 |
| | 4.5 | -1.198 | 0.604 | -1.939 | -13.022 | 0.290 | 0.231 | 0.391 |
| | 5 | -1.199 | 0.606 | -1.943 | -13.110 | 0.297 | 0.236 | 0.388 |
| **z=0.90** | 0.1 | -0.107 | 0.570 | -2.172 | -14.775 | 0.266 | 0.211 | 0.417 |
| | 0.2 | -0.360 | 0.604 | -2.065 | -16.236 | 0.300 | 0.237 | 0.411 |
| | 0.3 | -0.992 | 0.629 | -1.833 | -13.766 | 0.308 | 0.256 | 0.377 |
| | 0.4 | -1.338 | 0.653 | -1.732 | -12.584 | 0.296 | 0.249 | 0.364 |
| | 0.5 | -1.546 | 0.670 | -1.688 | -12.488 | 0.308 | 0.236 | 0.357 |
| | 0.75 | -1.880 | 0.701 | -1.646 | -11.359 | 0.371 | 0.251 | 0.350 |
| | 1 | -2.012 | 0.712 | -1.640 | -11.186 | 0.379 | 0.273 | 0.359 |
| | 1.5 | -2.198 | 0.719 | -1.604 | -11.556 | 0.357 | 0.278 | 0.354 |
| | 2 | -2.393 | 0.721 | -1.555 | -10.482 | 0.351 | 0.277 | 0.351 |
| | 2.5 | -2.462 | 0.727 | -1.564 | -10.950 | 0.338 | 0.268 | 0.349 |
| | 3 | -2.471 | 0.724 | -1.572 | -11.301 | 0.333 | 0.254 | 0.354 |
| | 3.5 | -2.553 | 0.728 | -1.566 | -11.171 | 0.340 | 0.257 | 0.352 |
| | 4 | -2.622 | 0.732 | -1.561 | -11.094 | 0.349 | 0.255 | 0.342 |
| | 4.5 | -2.678 | 0.736 | -1.565 | -10.817 | 0.342 | 0.249 | 0.343 |
| | 5 | -2.742 | 0.740 | -1.560 | -10.317 | 0.346 | 0.251 | 0.341 |
| **z=1.00** | 0.1 | 0.022 | 0.565 | -2.206 | -14.938 | 0.261 | 0.209 | 0.423 |
| | 0.2 | -0.202 | 0.596 | -2.093 | -16.272 | 0.297 | 0.235 | 0.414 |
| | 0.3 | -0.767 | 0.613 | -1.864 | -13.630 | 0.302 | 0.248 | 0.378 |
| | 0.4 | -1.034 | 0.631 | -1.779 | -12.322 | 0.287 | 0.235 | 0.366 |
| | 0.5 | -1.133 | 0.639 | -1.756 | -12.464 | 0.296 | 0.225 | 0.358 |
| | 0.75 | -1.300 | 0.660 | -1.751 | -11.620 | 0.356 | 0.238 | 0.359 |
| | 1 | -1.292 | 0.662 | -1.769 | -11.744 | 0.351 | 0.258 | 0.372 |
| | 1.5 | -1.321 | 0.655 | -1.744 | -12.045 | 0.322 | 0.256 | 0.364 |
| | 2 | -1.336 | 0.646 | -1.730 | -11.382 | 0.322 | 0.253 | 0.363 |
| | 2.5 | -1.328 | 0.650 | -1.748 | -11.694 | 0.310 | 0.243 | 0.361 |
| | 3 | -1.251 | 0.644 | -1.773 | -12.329 | 0.316 | 0.237 | 0.366 |
| | 3.5 | -1.260 | 0.643 | -1.774 | -12.570 | 0.323 | 0.240 | 0.365 |
| | 4 | -1.264 | 0.642 | -1.777 | -12.707 | 0.331 | 0.243 | 0.359 |
| | 4.5 | -1.386 | 0.657 | -1.767 | -12.271 | 0.329 | 0.243 | 0.357 |
| | 5 | -1.444 | 0.657 | -1.746 | -11.802 | 0.333 | 0.246 | 0.356 |

*Table 31. Coefficients for Peak-Floor Acceleration, α=8 (εσ is the total standard deviation)*

| | **Period (s)** | **b1** | **b2** | **b3** | **b4** | **b5** | **b6** | **εσ** |
|---|---|---|---|---|---|---|---|---|
| **z=0.05** | 0.1 | -1.367 | 0.620 | -1.841 | -12.243 | 0.318 | 0.235 | 0.371 |
| | 0.2 | -1.374 | 0.620 | -1.837 | -12.216 | 0.316 | 0.234 | 0.369 |
| | 0.3 | -1.375 | 0.620 | -1.836 | -12.208 | 0.317 | 0.235 | 0.369 |
| | 0.4 | -1.379 | 0.621 | -1.838 | -12.221 | 0.318 | 0.234 | 0.370 |
| | 0.5 | -1.373 | 0.620 | -1.840 | -12.307 | 0.318 | 0.236 | 0.370 |
| | 0.75 | -1.382 | 0.621 | -1.837 | -12.334 | 0.317 | 0.236 | 0.370 |
| | 1 | -1.398 | 0.622 | -1.834 | -12.295 | 0.320 | 0.236 | 0.370 |
| | 1.5 | -1.443 | 0.627 | -1.829 | -12.397 | 0.322 | 0.238 | 0.369 |
| | 2 | -1.492 | 0.629 | -1.813 | -12.314 | 0.324 | 0.240 | 0.367 |
| | 2.5 | -1.518 | 0.631 | -1.809 | -12.374 | 0.325 | 0.243 | 0.367 |
| | 3 | -1.587 | 0.637 | -1.798 | -12.138 | 0.326 | 0.241 | 0.365 |
| | 3.5 | -1.623 | 0.640 | -1.790 | -12.070 | 0.321 | 0.243 | 0.364 |
| | 4 | -1.626 | 0.637 | -1.784 | -12.078 | 0.323 | 0.239 | 0.363 |
| | 4.5 | -1.651 | 0.636 | -1.774 | -11.901 | 0.323 | 0.239 | 0.361 |
| | 5 | -1.665 | 0.638 | -1.776 | -11.915 | 0.321 | 0.242 | 0.360 |
| **z=0.10** | 0.1 | -1.328 | 0.618 | -1.850 | -12.255 | 0.319 | 0.234 | 0.372 |
| | 0.2 | -1.353 | 0.618 | -1.836 | -12.184 | 0.312 | 0.233 | 0.369 |
| | 0.3 | -1.364 | 0.619 | -1.835 | -12.107 | 0.316 | 0.237 | 0.368 |
| | 0.4 | -1.365 | 0.620 | -1.838 | -12.044 | 0.316 | 0.231 | 0.369 |
| | 0.5 | -1.351 | 0.621 | -1.848 | -12.278 | 0.318 | 0.237 | 0.371 |
| | 0.75 | -1.360 | 0.618 | -1.837 | -12.275 | 0.317 | 0.239 | 0.370 |
| | 1 | -1.365 | 0.620 | -1.839 | -12.297 | 0.317 | 0.236 | 0.370 |
| | 1.5 | -1.427 | 0.630 | -1.839 | -12.611 | 0.318 | 0.238 | 0.367 |
| | 2 | -1.527 | 0.633 | -1.802 | -12.451 | 0.324 | 0.241 | 0.368 |
| | 2.5 | -1.621 | 0.644 | -1.793 | -12.757 | 0.333 | 0.253 | 0.368 |
| | 3 | -1.724 | 0.652 | -1.775 | -12.753 | 0.339 | 0.256 | 0.362 |
| | 3.5 | -1.912 | 0.671 | -1.743 | -12.561 | 0.337 | 0.264 | 0.364 |
| | 4 | -1.994 | 0.676 | -1.723 | -12.590 | 0.336 | 0.260 | 0.365 |
| | 4.5 | -2.096 | 0.681 | -1.697 | -12.382 | 0.331 | 0.257 | 0.358 |
| | 5 | -2.190 | 0.684 | -1.671 | -12.230 | 0.333 | 0.262 | 0.354 |
| **z=0.20** | 0.1 | -1.169 | 0.612 | -1.893 | -12.602 | 0.315 | 0.232 | 0.376 |
| | 0.2 | -1.203 | 0.613 | -1.866 | -12.680 | 0.297 | 0.232 | 0.371 |
| | 0.3 | -1.294 | 0.617 | -1.839 | -12.192 | 0.311 | 0.235 | 0.366 |
| | 0.4 | -1.263 | 0.617 | -1.847 | -12.090 | 0.315 | 0.230 | 0.368 |
| | 0.5 | -1.268 | 0.626 | -1.870 | -12.552 | 0.314 | 0.235 | 0.372 |
| | 0.75 | -1.281 | 0.617 | -1.837 | -12.421 | 0.315 | 0.240 | 0.368 |
| | 1 | -1.348 | 0.624 | -1.825 | -12.178 | 0.317 | 0.243 | 0.372 |
| | 1.5 | -1.415 | 0.636 | -1.833 | -13.311 | 0.316 | 0.250 | 0.363 |
| | 2 | -1.606 | 0.645 | -1.770 | -12.304 | 0.330 | 0.248 | 0.366 |
| | 2.5 | -1.703 | 0.654 | -1.757 | -12.969 | 0.332 | 0.252 | 0.361 |
| | 3 | -1.831 | 0.659 | -1.720 | -12.479 | 0.339 | 0.254 | 0.362 |
| | 3.5 | -2.017 | 0.675 | -1.685 | -12.381 | 0.345 | 0.261 | 0.357 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 4 | -2.146 | 0.690 | -1.674 | -12.286 | 0.338 | 0.263 | 0.355 |
| | 4.5 | -2.224 | 0.691 | -1.648 | -12.089 | 0.347 | 0.265 | 0.353 |
| | 5 | -2.310 | 0.698 | -1.639 | -11.922 | 0.347 | 0.260 | 0.351 |
| **z=0.30** | 0.1 | -0.950 | 0.604 | -1.954 | -13.168 | 0.304 | 0.228 | 0.383 |
| | 0.2 | -1.013 | 0.609 | -1.907 | -13.371 | 0.290 | 0.232 | 0.379 |
| | 0.3 | -1.186 | 0.613 | -1.840 | -12.561 | 0.296 | 0.232 | 0.365 |
| | 0.4 | -1.195 | 0.616 | -1.838 | -12.401 | 0.312 | 0.238 | 0.365 |
| | 0.5 | -1.259 | 0.636 | -1.862 | -12.968 | 0.319 | 0.234 | 0.371 |
| | 0.75 | -1.388 | 0.634 | -1.799 | -12.562 | 0.330 | 0.247 | 0.364 |
| | 1 | -1.570 | 0.645 | -1.753 | -11.804 | 0.328 | 0.252 | 0.364 |
| | 1.5 | -1.646 | 0.652 | -1.743 | -12.761 | 0.318 | 0.250 | 0.355 |
| | 2 | -1.843 | 0.667 | -1.715 | -12.108 | 0.336 | 0.250 | 0.355 |
| | 2.5 | -2.026 | 0.679 | -1.672 | -11.599 | 0.346 | 0.254 | 0.356 |
| | 3 | -2.093 | 0.680 | -1.657 | -11.781 | 0.346 | 0.259 | 0.351 |
| | 3.5 | -2.265 | 0.700 | -1.646 | -12.006 | 0.362 | 0.265 | 0.356 |
| | 4 | -2.434 | 0.722 | -1.633 | -11.849 | 0.355 | 0.269 | 0.359 |
| | 4.5 | -2.559 | 0.727 | -1.599 | -11.477 | 0.359 | 0.270 | 0.359 |
| | 5 | -2.629 | 0.728 | -1.585 | -11.558 | 0.359 | 0.277 | 0.354 |
| **z=0.40** | 0.1 | -0.734 | 0.594 | -2.009 | -13.544 | 0.293 | 0.223 | 0.392 |
| | 0.2 | -0.862 | 0.609 | -1.944 | -14.036 | 0.291 | 0.232 | 0.388 |
| | 0.3 | -1.138 | 0.616 | -1.836 | -12.940 | 0.291 | 0.235 | 0.365 |
| | 0.4 | -1.222 | 0.622 | -1.808 | -12.594 | 0.313 | 0.246 | 0.362 |
| | 0.5 | -1.353 | 0.651 | -1.829 | -13.182 | 0.330 | 0.240 | 0.365 |
| | 0.75 | -1.629 | 0.662 | -1.737 | -12.216 | 0.336 | 0.245 | 0.359 |
| | 1 | -1.777 | 0.662 | -1.684 | -11.450 | 0.336 | 0.258 | 0.353 |
| | 1.5 | -1.897 | 0.675 | -1.679 | -12.080 | 0.322 | 0.256 | 0.350 |
| | 2 | -2.029 | 0.690 | -1.684 | -12.150 | 0.347 | 0.254 | 0.352 |
| | 2.5 | -2.211 | 0.703 | -1.655 | -11.718 | 0.355 | 0.263 | 0.356 |
| | 3 | -2.280 | 0.701 | -1.634 | -11.416 | 0.358 | 0.267 | 0.360 |
| | 3.5 | -2.422 | 0.708 | -1.598 | -11.378 | 0.356 | 0.267 | 0.352 |
| | 4 | -2.540 | 0.720 | -1.588 | -11.905 | 0.355 | 0.282 | 0.351 |
| | 4.5 | -2.663 | 0.728 | -1.567 | -11.671 | 0.365 | 0.282 | 0.350 |
| | 5 | -2.799 | 0.738 | -1.549 | -11.318 | 0.360 | 0.283 | 0.349 |
| **z=0.50** | 0.1 | -0.550 | 0.586 | -2.056 | -13.901 | 0.284 | 0.218 | 0.400 |
| | 0.2 | -0.747 | 0.610 | -1.973 | -14.719 | 0.295 | 0.234 | 0.395 |
| | 0.3 | -1.162 | 0.625 | -1.818 | -13.097 | 0.291 | 0.240 | 0.367 |
| | 0.4 | -1.334 | 0.634 | -1.763 | -12.434 | 0.310 | 0.244 | 0.360 |
| | 0.5 | -1.506 | 0.665 | -1.772 | -12.968 | 0.334 | 0.245 | 0.357 |
| | 0.75 | -1.819 | 0.684 | -1.692 | -11.635 | 0.346 | 0.243 | 0.354 |
| | 1 | -1.945 | 0.680 | -1.645 | -11.079 | 0.341 | 0.257 | 0.351 |
| | 1.5 | -2.011 | 0.684 | -1.654 | -11.299 | 0.336 | 0.259 | 0.349 |
| | 2 | -2.086 | 0.698 | -1.677 | -11.691 | 0.334 | 0.251 | 0.359 |
| | 2.5 | -2.121 | 0.689 | -1.653 | -11.618 | 0.345 | 0.257 | 0.353 |
| | 3 | -2.169 | 0.689 | -1.654 | -11.477 | 0.355 | 0.260 | 0.351 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3.5 | -2.284 | 0.697 | -1.637 | -11.176 | 0.361 | 0.270 | 0.355 |
| | 4 | -2.401 | 0.711 | -1.625 | -11.149 | 0.353 | 0.269 | 0.360 |
| | 4.5 | -2.436 | 0.709 | -1.614 | -11.564 | 0.349 | 0.272 | 0.360 |
| | 5 | -2.497 | 0.715 | -1.617 | -11.799 | 0.345 | 0.275 | 0.354 |
| **z=0.60** | 0.1 | -0.402 | 0.580 | -2.094 | -14.244 | 0.278 | 0.215 | 0.405 |
| | 0.2 | -0.665 | 0.613 | -1.997 | -15.349 | 0.302 | 0.237 | 0.401 |
| | 0.3 | -1.212 | 0.634 | -1.799 | -13.175 | 0.298 | 0.251 | 0.370 |
| | 0.4 | -1.462 | 0.650 | -1.725 | -12.508 | 0.300 | 0.246 | 0.359 |
| | 0.5 | -1.639 | 0.672 | -1.710 | -12.585 | 0.325 | 0.238 | 0.353 |
| | 0.75 | -1.940 | 0.696 | -1.662 | -11.574 | 0.370 | 0.250 | 0.351 |
| | 1 | -2.079 | 0.702 | -1.638 | -10.822 | 0.363 | 0.259 | 0.355 |
| | 1.5 | -2.119 | 0.696 | -1.634 | -11.443 | 0.334 | 0.270 | 0.349 |
| | 2 | -2.176 | 0.694 | -1.631 | -11.154 | 0.345 | 0.262 | 0.353 |
| | 2.5 | -2.261 | 0.705 | -1.641 | -11.383 | 0.348 | 0.265 | 0.357 |
| | 3 | -2.306 | 0.707 | -1.638 | -12.002 | 0.351 | 0.261 | 0.362 |
| | 3.5 | -2.435 | 0.716 | -1.622 | -11.933 | 0.350 | 0.265 | 0.359 |
| | 4 | -2.555 | 0.727 | -1.613 | -12.323 | 0.348 | 0.269 | 0.357 |
| | 4.5 | -2.770 | 0.743 | -1.571 | -11.668 | 0.352 | 0.281 | 0.354 |
| | 5 | -2.944 | 0.755 | -1.537 | -11.126 | 0.349 | 0.285 | 0.356 |
| **z=0.70** | 0.1 | -0.287 | 0.576 | -2.125 | -14.501 | 0.273 | 0.213 | 0.410 |
| | 0.2 | -0.575 | 0.614 | -2.023 | -15.939 | 0.304 | 0.240 | 0.406 |
| | 0.3 | -1.234 | 0.644 | -1.800 | -13.627 | 0.311 | 0.263 | 0.375 |
| | 0.4 | -1.601 | 0.669 | -1.697 | -12.677 | 0.298 | 0.257 | 0.365 |
| | 0.5 | -1.852 | 0.690 | -1.646 | -12.218 | 0.314 | 0.238 | 0.358 |
| | 0.75 | -2.189 | 0.719 | -1.604 | -10.878 | 0.372 | 0.245 | 0.347 |
| | 1 | -2.252 | 0.721 | -1.610 | -10.538 | 0.381 | 0.268 | 0.350 |
| | 1.5 | -2.243 | 0.714 | -1.627 | -10.976 | 0.356 | 0.263 | 0.359 |
| | 2 | -2.220 | 0.696 | -1.620 | -10.645 | 0.339 | 0.265 | 0.361 |
| | 2.5 | -2.158 | 0.681 | -1.630 | -11.261 | 0.327 | 0.264 | 0.353 |
| | 3 | -2.147 | 0.681 | -1.655 | -11.779 | 0.334 | 0.258 | 0.351 |
| | 3.5 | -2.208 | 0.688 | -1.659 | -12.122 | 0.346 | 0.255 | 0.356 |
| | 4 | -2.307 | 0.704 | -1.668 | -12.068 | 0.335 | 0.252 | 0.360 |
| | 4.5 | -2.388 | 0.706 | -1.647 | -12.117 | 0.339 | 0.257 | 0.358 |
| | 5 | -2.474 | 0.711 | -1.631 | -12.228 | 0.350 | 0.263 | 0.353 |
| **z=0.80** | 0.1 | -0.207 | 0.573 | -2.147 | -14.612 | 0.270 | 0.213 | 0.413 |
| | 0.2 | -0.453 | 0.607 | -2.047 | -16.101 | 0.299 | 0.237 | 0.408 |
| | 0.3 | -1.100 | 0.635 | -1.819 | -13.863 | 0.310 | 0.260 | 0.375 |
| | 0.4 | -1.506 | 0.665 | -1.711 | -12.952 | 0.316 | 0.260 | 0.366 |
| | 0.5 | -1.787 | 0.692 | -1.666 | -12.815 | 0.332 | 0.248 | 0.359 |
| | 0.75 | -2.298 | 0.727 | -1.555 | -10.774 | 0.359 | 0.249 | 0.348 |
| | 1 | -2.431 | 0.733 | -1.551 | -10.062 | 0.369 | 0.263 | 0.342 |
| | 1.5 | -2.365 | 0.720 | -1.585 | -10.531 | 0.365 | 0.264 | 0.351 |
| | 2 | -2.284 | 0.711 | -1.626 | -10.677 | 0.359 | 0.257 | 0.361 |
| | 2.5 | -2.230 | 0.699 | -1.642 | -10.939 | 0.354 | 0.260 | 0.366 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3 | -2.205 | 0.690 | -1.647 | -11.288 | 0.356 | 0.265 | 0.366 |
| | 3.5 | -2.249 | 0.690 | -1.642 | -11.521 | 0.343 | 0.265 | 0.364 |
| | 4 | -2.318 | 0.700 | -1.651 | -12.033 | 0.331 | 0.270 | 0.364 |
| | 4.5 | -2.369 | 0.700 | -1.642 | -12.182 | 0.329 | 0.274 | 0.361 |
| | 5 | -2.488 | 0.706 | -1.618 | -12.130 | 0.327 | 0.273 | 0.359 |
| **z=0.90** | 0.1 | -0.158 | 0.572 | -2.160 | -14.609 | 0.269 | 0.212 | 0.415 |
| | 0.2 | -0.345 | 0.599 | -2.065 | -15.965 | 0.293 | 0.234 | 0.408 |
| | 0.3 | -0.893 | 0.618 | -1.854 | -13.980 | 0.304 | 0.250 | 0.375 |
| | 0.4 | -1.233 | 0.645 | -1.763 | -13.130 | 0.314 | 0.254 | 0.366 |
| | 0.5 | -1.476 | 0.672 | -1.730 | -13.226 | 0.331 | 0.244 | 0.360 |
| | 0.75 | -2.019 | 0.713 | -1.616 | -11.799 | 0.365 | 0.258 | 0.353 |
| | 1 | -2.392 | 0.740 | -1.551 | -10.715 | 0.373 | 0.278 | 0.352 |
| | 1.5 | -2.683 | 0.755 | -1.502 | -10.905 | 0.359 | 0.279 | 0.349 |
| | 2 | -2.896 | 0.769 | -1.486 | -10.718 | 0.364 | 0.273 | 0.346 |
| | 2.5 | -2.999 | 0.771 | -1.480 | -10.032 | 0.376 | 0.273 | 0.342 |
| | 3 | -3.015 | 0.770 | -1.499 | -10.252 | 0.385 | 0.275 | 0.340 |
| | 3.5 | -3.076 | 0.776 | -1.510 | -10.641 | 0.394 | 0.274 | 0.344 |
| | 4 | -3.131 | 0.777 | -1.504 | -10.458 | 0.381 | 0.270 | 0.350 |
| | 4.5 | -3.204 | 0.783 | -1.508 | -10.729 | 0.377 | 0.276 | 0.352 |
| | 5 | -3.235 | 0.780 | -1.508 | -10.686 | 0.377 | 0.280 | 0.344 |
| **z=1.00** | 0.1 | -0.123 | 0.570 | -2.169 | -14.582 | 0.267 | 0.212 | 0.417 |
| | 0.2 | -0.268 | 0.594 | -2.079 | -15.765 | 0.288 | 0.231 | 0.409 |
| | 0.3 | -0.729 | 0.605 | -1.880 | -13.769 | 0.296 | 0.243 | 0.376 |
| | 0.4 | -0.981 | 0.625 | -1.808 | -12.785 | 0.306 | 0.244 | 0.367 |
| | 0.5 | -1.114 | 0.642 | -1.797 | -12.909 | 0.316 | 0.235 | 0.362 |
| | 0.75 | -1.356 | 0.659 | -1.738 | -12.091 | 0.344 | 0.239 | 0.357 |
| | 1 | -1.528 | 0.666 | -1.693 | -10.917 | 0.340 | 0.254 | 0.357 |
| | 1.5 | -1.548 | 0.667 | -1.706 | -11.765 | 0.333 | 0.254 | 0.355 |
| | 2 | -1.625 | 0.668 | -1.692 | -11.424 | 0.341 | 0.257 | 0.358 |
| | 2.5 | -1.696 | 0.675 | -1.692 | -11.823 | 0.345 | 0.264 | 0.360 |
| | 3 | -1.745 | 0.676 | -1.686 | -11.989 | 0.348 | 0.260 | 0.358 |
| | 3.5 | -1.890 | 0.690 | -1.671 | -11.832 | 0.350 | 0.261 | 0.359 |
| | 4 | -2.027 | 0.703 | -1.648 | -11.903 | 0.344 | 0.262 | 0.361 |
| | 4.5 | -2.120 | 0.710 | -1.637 | -12.110 | 0.346 | 0.279 | 0.358 |
| | 5 | -2.267 | 0.720 | -1.609 | -11.908 | 0.348 | 0.277 | 0.357 |

*Table 32. Coefficients for Peak-Floor Acceleration, α=30 (εσ is the total standard deviation)*

| | **Period (s)** | **b1** | **b2** | **b3** | **b4** | **b5** | **b6** | **εσ** |
|---|---|---|---|---|---|---|---|---|
| **z=0.05** | 0.1 | -1.353 | 0.620 | -1.844 | -12.259 | 0.319 | 0.235 | 0.371 |
| | 0.2 | -1.373 | 0.619 | -1.834 | -12.240 | 0.315 | 0.234 | 0.369 |
| | 0.3 | -1.388 | 0.620 | -1.830 | -12.105 | 0.319 | 0.236 | 0.369 |
| | 0.4 | -1.381 | 0.622 | -1.839 | -12.358 | 0.319 | 0.235 | 0.369 |
| | 0.5 | -1.397 | 0.624 | -1.836 | -12.376 | 0.321 | 0.235 | 0.370 |
| | 0.75 | -1.443 | 0.626 | -1.824 | -12.335 | 0.322 | 0.241 | 0.369 |
| | 1 | -1.513 | 0.632 | -1.811 | -12.464 | 0.326 | 0.243 | 0.368 |
| | 1.5 | -1.630 | 0.638 | -1.782 | -12.108 | 0.327 | 0.246 | 0.364 |
| | 2 | -1.710 | 0.643 | -1.764 | -11.963 | 0.324 | 0.244 | 0.361 |
| | 2.5 | -1.763 | 0.645 | -1.754 | -11.927 | 0.325 | 0.246 | 0.358 |
| | 3 | -1.808 | 0.645 | -1.740 | -11.620 | 0.325 | 0.245 | 0.357 |
| | 3.5 | -1.850 | 0.652 | -1.744 | -11.585 | 0.330 | 0.239 | 0.358 |
| | 4 | -1.828 | 0.648 | -1.752 | -11.598 | 0.331 | 0.243 | 0.359 |
| | 4.5 | -1.815 | 0.648 | -1.760 | -11.734 | 0.328 | 0.236 | 0.359 |
| | 5 | -1.799 | 0.645 | -1.763 | -11.722 | 0.330 | 0.237 | 0.360 |
| **z=0.10** | 0.1 | -1.274 | 0.616 | -1.864 | -12.333 | 0.318 | 0.233 | 0.373 |
| | 0.2 | -1.319 | 0.619 | -1.844 | -12.355 | 0.307 | 0.232 | 0.369 |
| | 0.3 | -1.362 | 0.620 | -1.830 | -11.913 | 0.316 | 0.234 | 0.367 |
| | 0.4 | -1.321 | 0.621 | -1.852 | -12.518 | 0.314 | 0.235 | 0.368 |
| | 0.5 | -1.348 | 0.625 | -1.849 | -12.461 | 0.318 | 0.229 | 0.371 |
| | 0.75 | -1.409 | 0.625 | -1.824 | -12.389 | 0.322 | 0.245 | 0.369 |
| | 1 | -1.482 | 0.632 | -1.812 | -12.690 | 0.324 | 0.247 | 0.369 |
| | 1.5 | -1.677 | 0.647 | -1.772 | -12.686 | 0.339 | 0.256 | 0.363 |
| | 2 | -1.924 | 0.669 | -1.727 | -12.567 | 0.335 | 0.260 | 0.365 |
| | 2.5 | -2.168 | 0.691 | -1.689 | -12.613 | 0.332 | 0.267 | 0.361 |
| | 3 | -2.409 | 0.702 | -1.620 | -12.069 | 0.334 | 0.271 | 0.355 |
| | 3.5 | -2.597 | 0.721 | -1.598 | -12.035 | 0.342 | 0.270 | 0.356 |
| | 4 | -2.804 | 0.736 | -1.560 | -11.408 | 0.353 | 0.278 | 0.352 |
| | 4.5 | -2.921 | 0.746 | -1.545 | -11.179 | 0.354 | 0.270 | 0.353 |
| | 5 | -3.033 | 0.757 | -1.534 | -11.100 | 0.353 | 0.269 | 0.351 |
| **z=0.20** | 0.1 | -1.044 | 0.608 | -1.929 | -12.894 | 0.309 | 0.230 | 0.381 |
| | 0.2 | -1.086 | 0.611 | -1.895 | -13.187 | 0.294 | 0.230 | 0.375 |
| | 0.3 | -1.219 | 0.616 | -1.846 | -12.297 | 0.304 | 0.234 | 0.365 |
| | 0.4 | -1.219 | 0.623 | -1.861 | -12.944 | 0.310 | 0.235 | 0.366 |
| | 0.5 | -1.279 | 0.632 | -1.855 | -12.811 | 0.315 | 0.229 | 0.375 |
| | 0.75 | -1.437 | 0.640 | -1.810 | -12.751 | 0.329 | 0.251 | 0.364 |
| | 1 | -1.578 | 0.641 | -1.750 | -12.179 | 0.331 | 0.254 | 0.364 |
| | 1.5 | -1.820 | 0.668 | -1.731 | -12.714 | 0.338 | 0.258 | 0.358 |
| | 2 | -2.097 | 0.690 | -1.676 | -12.301 | 0.336 | 0.260 | 0.357 |
| | 2.5 | -2.316 | 0.704 | -1.631 | -11.922 | 0.347 | 0.258 | 0.352 |
| | 3 | -2.492 | 0.713 | -1.594 | -11.474 | 0.358 | 0.265 | 0.352 |
| | 3.5 | -2.624 | 0.722 | -1.569 | -11.346 | 0.361 | 0.269 | 0.350 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 4 | -2.782 | 0.736 | -1.550 | -11.109 | 0.361 | 0.268 | 0.349 |
| | 4.5 | -2.838 | 0.742 | -1.560 | -11.064 | 0.360 | 0.271 | 0.350 |
| | 5 | -2.925 | 0.743 | -1.533 | -10.551 | 0.362 | 0.272 | 0.348 |
| **z=0.30** | 0.1 | -0.817 | 0.598 | -1.988 | -13.347 | 0.298 | 0.225 | 0.389 |
| | 0.2 | -0.914 | 0.609 | -1.933 | -13.831 | 0.292 | 0.233 | 0.384 |
| | 0.3 | -1.141 | 0.617 | -1.848 | -12.782 | 0.297 | 0.237 | 0.364 |
| | 0.4 | -1.233 | 0.629 | -1.836 | -12.882 | 0.311 | 0.241 | 0.363 |
| | 0.5 | -1.312 | 0.640 | -1.826 | -12.943 | 0.323 | 0.233 | 0.373 |
| | 0.75 | -1.570 | 0.656 | -1.761 | -12.738 | 0.341 | 0.251 | 0.359 |
| | 1 | -1.767 | 0.659 | -1.686 | -11.417 | 0.334 | 0.256 | 0.360 |
| | 1.5 | -1.970 | 0.679 | -1.674 | -12.202 | 0.345 | 0.261 | 0.356 |
| | 2 | -2.301 | 0.712 | -1.633 | -11.657 | 0.352 | 0.270 | 0.358 |
| | 2.5 | -2.498 | 0.725 | -1.594 | -11.679 | 0.351 | 0.264 | 0.358 |
| | 3 | -2.717 | 0.736 | -1.551 | -11.322 | 0.363 | 0.280 | 0.356 |
| | 3.5 | -2.912 | 0.752 | -1.520 | -11.245 | 0.366 | 0.290 | 0.357 |
| | 4 | -3.108 | 0.768 | -1.491 | -11.090 | 0.366 | 0.289 | 0.357 |
| | 4.5 | -3.241 | 0.782 | -1.487 | -11.274 | 0.362 | 0.286 | 0.360 |
| | 5 | -3.438 | 0.799 | -1.457 | -10.751 | 0.365 | 0.290 | 0.361 |
| **z=0.40** | 0.1 | -0.628 | 0.589 | -2.036 | -13.711 | 0.288 | 0.220 | 0.397 |
| | 0.2 | -0.795 | 0.610 | -1.962 | -14.425 | 0.293 | 0.234 | 0.391 |
| | 0.3 | -1.148 | 0.623 | -1.832 | -13.101 | 0.295 | 0.239 | 0.365 |
| | 0.4 | -1.303 | 0.638 | -1.797 | -12.826 | 0.313 | 0.245 | 0.359 |
| | 0.5 | -1.441 | 0.655 | -1.784 | -12.885 | 0.332 | 0.241 | 0.367 |
| | 0.75 | -1.774 | 0.681 | -1.716 | -12.488 | 0.343 | 0.251 | 0.355 |
| | 1 | -2.004 | 0.684 | -1.636 | -11.268 | 0.349 | 0.262 | 0.351 |
| | 1.5 | -2.224 | 0.705 | -1.622 | -12.169 | 0.349 | 0.273 | 0.354 |
| | 2 | -2.580 | 0.745 | -1.597 | -11.655 | 0.351 | 0.273 | 0.357 |
| | 2.5 | -2.794 | 0.749 | -1.537 | -11.082 | 0.353 | 0.281 | 0.353 |
| | 3 | -3.000 | 0.760 | -1.499 | -10.821 | 0.353 | 0.282 | 0.357 |
| | 3.5 | -3.171 | 0.773 | -1.473 | -11.099 | 0.355 | 0.281 | 0.356 |
| | 4 | -3.381 | 0.794 | -1.451 | -11.015 | 0.370 | 0.290 | 0.357 |
| | 4.5 | -3.499 | 0.803 | -1.441 | -10.802 | 0.363 | 0.285 | 0.358 |
| | 5 | -3.663 | 0.817 | -1.419 | -10.614 | 0.372 | 0.279 | 0.355 |
| **z=0.50** | 0.1 | -0.479 | 0.583 | -2.074 | -14.034 | 0.281 | 0.216 | 0.403 |
| | 0.2 | -0.702 | 0.611 | -1.986 | -15.021 | 0.299 | 0.237 | 0.397 |
| | 0.3 | -1.173 | 0.630 | -1.815 | -13.243 | 0.293 | 0.244 | 0.367 |
| | 0.4 | -1.386 | 0.647 | -1.762 | -12.843 | 0.307 | 0.244 | 0.358 |
| | 0.5 | -1.547 | 0.665 | -1.743 | -12.752 | 0.331 | 0.240 | 0.360 |
| | 0.75 | -1.885 | 0.692 | -1.681 | -12.013 | 0.352 | 0.250 | 0.353 |
| | 1 | -2.110 | 0.697 | -1.612 | -10.841 | 0.357 | 0.260 | 0.348 |
| | 1.5 | -2.239 | 0.704 | -1.608 | -11.416 | 0.360 | 0.277 | 0.356 |
| | 2 | -2.455 | 0.727 | -1.601 | -11.659 | 0.351 | 0.270 | 0.353 |
| | 2.5 | -2.667 | 0.740 | -1.561 | -11.174 | 0.355 | 0.271 | 0.353 |
| | 3 | -2.818 | 0.747 | -1.539 | -11.100 | 0.355 | 0.277 | 0.355 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3.5 | -2.920 | 0.751 | -1.523 | -11.369 | 0.357 | 0.283 | 0.353 |
| | 4 | -3.107 | 0.764 | -1.491 | -11.057 | 0.363 | 0.282 | 0.350 |
| | 4.5 | -3.241 | 0.777 | -1.483 | -11.208 | 0.364 | 0.289 | 0.354 |
| | 5 | -3.379 | 0.792 | -1.476 | -11.054 | 0.367 | 0.288 | 0.354 |
| **z=0.60** | 0.1 | -0.359 | 0.579 | -2.105 | -14.302 | 0.276 | 0.214 | 0.407 |
| | 0.2 | -0.633 | 0.613 | -2.006 | -15.527 | 0.304 | 0.239 | 0.403 |
| | 0.3 | -1.215 | 0.638 | -1.801 | -13.349 | 0.298 | 0.253 | 0.371 |
| | 0.4 | -1.498 | 0.658 | -1.723 | -12.894 | 0.301 | 0.250 | 0.360 |
| | 0.5 | -1.709 | 0.677 | -1.686 | -12.560 | 0.322 | 0.236 | 0.354 |
| | 0.75 | -2.072 | 0.711 | -1.638 | -11.562 | 0.365 | 0.244 | 0.351 |
| | 1 | -2.273 | 0.719 | -1.591 | -10.798 | 0.369 | 0.262 | 0.351 |
| | 1.5 | -2.414 | 0.721 | -1.581 | -11.283 | 0.371 | 0.284 | 0.350 |
| | 2 | -2.640 | 0.743 | -1.564 | -10.994 | 0.347 | 0.275 | 0.359 |
| | 2.5 | -2.782 | 0.749 | -1.541 | -11.644 | 0.338 | 0.269 | 0.356 |
| | 3 | -3.036 | 0.770 | -1.515 | -11.519 | 0.359 | 0.287 | 0.360 |
| | 3.5 | -3.230 | 0.789 | -1.499 | -11.199 | 0.345 | 0.279 | 0.366 |
| | 4 | -3.448 | 0.807 | -1.467 | -10.978 | 0.344 | 0.290 | 0.365 |
| | 4.5 | -3.594 | 0.816 | -1.441 | -10.900 | 0.342 | 0.285 | 0.369 |
| | 5 | -3.802 | 0.834 | -1.411 | -10.918 | 0.346 | 0.289 | 0.371 |
| **z=0.70** | 0.1 | -0.265 | 0.575 | -2.131 | -14.529 | 0.272 | 0.213 | 0.411 |
| | 0.2 | -0.544 | 0.612 | -2.029 | -15.952 | 0.303 | 0.239 | 0.406 |
| | 0.3 | -1.196 | 0.642 | -1.806 | -13.658 | 0.309 | 0.261 | 0.376 |
| | 0.4 | -1.585 | 0.670 | -1.701 | -12.854 | 0.301 | 0.256 | 0.365 |
| | 0.5 | -1.836 | 0.689 | -1.644 | -12.389 | 0.310 | 0.239 | 0.356 |
| | 0.75 | -2.261 | 0.728 | -1.588 | -11.140 | 0.372 | 0.246 | 0.346 |
| | 1 | -2.410 | 0.735 | -1.572 | -10.665 | 0.385 | 0.265 | 0.350 |
| | 1.5 | -2.588 | 0.744 | -1.558 | -10.876 | 0.377 | 0.281 | 0.355 |
| | 2 | -2.724 | 0.745 | -1.541 | -10.821 | 0.357 | 0.286 | 0.354 |
| | 2.5 | -2.836 | 0.745 | -1.517 | -10.843 | 0.338 | 0.276 | 0.352 |
| | 3 | -2.922 | 0.749 | -1.518 | -11.465 | 0.346 | 0.285 | 0.355 |
| | 3.5 | -3.047 | 0.761 | -1.515 | -11.791 | 0.344 | 0.275 | 0.352 |
| | 4 | -3.262 | 0.782 | -1.497 | -11.325 | 0.354 | 0.274 | 0.353 |
| | 4.5 | -3.381 | 0.794 | -1.494 | -11.437 | 0.355 | 0.277 | 0.352 |
| | 5 | -3.505 | 0.798 | -1.467 | -10.888 | 0.369 | 0.279 | 0.352 |
| **z=0.80** | 0.1 | -0.197 | 0.572 | -2.149 | -14.654 | 0.270 | 0.213 | 0.413 |
| | 0.2 | -0.435 | 0.604 | -2.047 | -16.014 | 0.297 | 0.236 | 0.407 |
| | 0.3 | -1.061 | 0.631 | -1.824 | -13.873 | 0.311 | 0.258 | 0.375 |
| | 0.4 | -1.461 | 0.663 | -1.724 | -13.198 | 0.316 | 0.260 | 0.364 |
| | 0.5 | -1.753 | 0.689 | -1.669 | -12.604 | 0.323 | 0.244 | 0.362 |
| | 0.75 | -2.291 | 0.730 | -1.563 | -11.275 | 0.351 | 0.254 | 0.350 |
| | 1 | -2.518 | 0.743 | -1.532 | -10.532 | 0.377 | 0.269 | 0.341 |
| | 1.5 | -2.631 | 0.749 | -1.541 | -10.872 | 0.386 | 0.278 | 0.349 |
| | 2 | -2.784 | 0.763 | -1.548 | -10.696 | 0.364 | 0.270 | 0.357 |
| | 2.5 | -2.878 | 0.757 | -1.521 | -10.653 | 0.360 | 0.277 | 0.355 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3 | -2.986 | 0.755 | -1.497 | -10.671 | 0.357 | 0.290 | 0.357 |
| | 3.5 | -3.061 | 0.757 | -1.494 | -10.938 | 0.345 | 0.289 | 0.356 |
| | 4 | -3.225 | 0.771 | -1.475 | -11.040 | 0.338 | 0.291 | 0.355 |
| | 4.5 | -3.314 | 0.782 | -1.484 | -11.488 | 0.333 | 0.287 | 0.358 |
| | 5 | -3.519 | 0.807 | -1.470 | -11.364 | 0.334 | 0.283 | 0.357 |
| **z=0.90** | 0.1 | -0.161 | 0.571 | -2.158 | -14.662 | 0.269 | 0.212 | 0.414 |
| | 0.2 | -0.353 | 0.598 | -2.059 | -15.881 | 0.293 | 0.232 | 0.408 |
| | 0.3 | -0.901 | 0.619 | -1.853 | -13.943 | 0.304 | 0.252 | 0.374 |
| | 0.4 | -1.239 | 0.645 | -1.763 | -13.276 | 0.309 | 0.253 | 0.364 |
| | 0.5 | -1.490 | 0.671 | -1.722 | -12.965 | 0.322 | 0.242 | 0.362 |
| | 0.75 | -2.074 | 0.722 | -1.618 | -12.110 | 0.360 | 0.260 | 0.353 |
| | 1 | -2.447 | 0.744 | -1.541 | -10.787 | 0.371 | 0.276 | 0.352 |
| | 1.5 | -2.909 | 0.777 | -1.468 | -10.894 | 0.371 | 0.291 | 0.354 |
| | 2 | -3.321 | 0.813 | -1.424 | -10.490 | 0.371 | 0.292 | 0.358 |
| | 2.5 | -3.607 | 0.838 | -1.400 | -10.191 | 0.372 | 0.282 | 0.361 |
| | 3 | -3.810 | 0.852 | -1.381 | -10.486 | 0.380 | 0.293 | 0.362 |
| | 3.5 | -3.957 | 0.859 | -1.366 | -10.691 | 0.386 | 0.294 | 0.364 |
| | 4 | -4.174 | 0.883 | -1.359 | -10.644 | 0.388 | 0.283 | 0.365 |
| | 4.5 | -4.305 | 0.890 | -1.347 | -10.636 | 0.393 | 0.293 | 0.365 |
| | 5 | -4.456 | 0.897 | -1.324 | -10.042 | 0.399 | 0.302 | 0.363 |
| **z=1.00** | 0.1 | -0.147 | 0.570 | -2.162 | -14.650 | 0.268 | 0.212 | 0.415 |
| | 0.2 | -0.322 | 0.595 | -2.064 | -15.738 | 0.291 | 0.231 | 0.408 |
| | 0.3 | -0.815 | 0.611 | -1.867 | -13.817 | 0.301 | 0.249 | 0.375 |
| | 0.4 | -1.102 | 0.633 | -1.786 | -13.047 | 0.303 | 0.247 | 0.364 |
| | 0.5 | -1.288 | 0.653 | -1.757 | -12.759 | 0.314 | 0.234 | 0.362 |
| | 0.75 | -1.656 | 0.682 | -1.685 | -12.031 | 0.345 | 0.247 | 0.352 |
| | 1 | -1.843 | 0.688 | -1.637 | -10.990 | 0.353 | 0.259 | 0.352 |
| | 1.5 | -2.016 | 0.703 | -1.630 | -11.745 | 0.364 | 0.272 | 0.354 |
| | 2 | -2.293 | 0.728 | -1.599 | -11.243 | 0.359 | 0.275 | 0.360 |
| | 2.5 | -2.450 | 0.735 | -1.572 | -11.406 | 0.350 | 0.276 | 0.357 |
| | 3 | -2.659 | 0.749 | -1.539 | -11.395 | 0.355 | 0.284 | 0.358 |
| | 3.5 | -2.812 | 0.759 | -1.518 | -11.331 | 0.352 | 0.286 | 0.358 |
| | 4 | -3.053 | 0.780 | -1.481 | -10.961 | 0.355 | 0.289 | 0.360 |
| | 4.5 | -3.171 | 0.793 | -1.480 | -11.089 | 0.357 | 0.288 | 0.359 |
| | 5 | -3.343 | 0.810 | -1.464 | -10.988 | 0.355 | 0.286 | 0.360 |

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