

## Chapter 2

# Rapid Earthquake Loss Assessment After Damaging Earthquakes

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**Abstract** This article summarizes the work done over last decades regarding the development of new approaches and setting up of new applications for earthquake rapid response systems that function to estimate earthquake losses in quasi real time after an earthquake. After a critical discussion of relevant earthquake loss estimation methodologies, the essential features and the characteristics of the available loss estimation software are summarized. Currently operating near real time loss estimation tools can be classified under two main categories depending on the size of area they cover: Global and Local Systems. For the global or regional near real time loss estimation systems: GDACS, WAPMERR, PAGER, ELER and SELENA methodologies are. Examples are provided for the local rapid earthquake loss estimation systems including: Taiwan Earthquake Rapid Reporting System, Real-time Earthquake Assessment Disaster System in Yokohama, Real Time Earthquake Disaster Mitigation System of the Tokyo Gas Co., IGDAS Earthquake Protection System and Istanbul Earthquake Rapid Response System.

## 2.1 Introduction

As illustrated in Fig. 2.1 (after Böse 2006), management of earthquake risks is a process that involves pre-, co- and post-seismic phases. Earthquake Early Warning (EEW) systems are involved in the co-seismic phase. These involve the generation of real time ground motion estimation maps as products of real-time seismology

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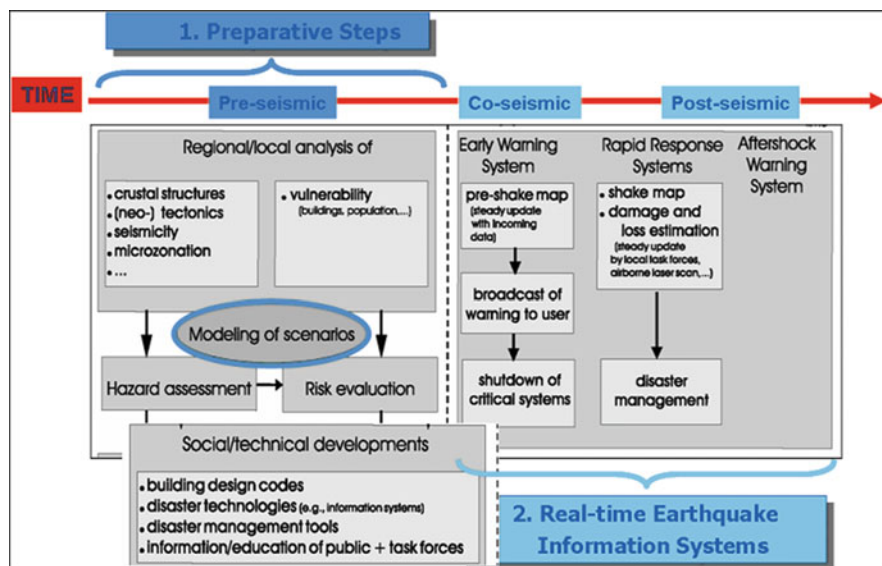


Fig. 2.1 Pre- co- and post-earthquake risk management activities (After Böse 2006)

and/or generation of alarm signals directly from on-line instrumental data. The Rapid Response Systems take part immediately after the earthquake and provide assessment of the distribution of ground shaking intensity (so-called ShakeMaps) and information on the physical (buildings) damage, casualties (fatalities) and economic losses. This rapid information on the consequences of the earthquake can serve to direct the search and rescue teams to the areas most needed and assist civil protection authorities in the emergency action. As such, the need for a rapid loss estimate after an earthquake has been recognized and requested by governments and international agencies.

This study will critically review the existing earthquake rapid response systems and methodologies that serve to produce earthquake loss information (building damages, casualties and economic losses) immediately after an earthquake.

Potential impact of large earthquakes on urban societies can be reduced by timely and correct action after a disastrous earthquake. Modern technology permits measurements of strong ground shaking in near real-time for urban areas exposed to earthquake risk. The assessments of the distribution of strong ground motion, building damage and casualties can be made within few minutes after an earthquake. The ground motion measurement and data processing systems designed to provide this information are called Earthquake Rapid Response Systems.

The reduction of casualties in urban areas immediately following an earthquake can be improved if the location and severity of damages can be rapidly assessed by the information from Rapid Response Systems. Emergency management centers of both public and private sector with functions in the immediate post-earthquake

period (i.e. SAR, fire and emergency medical deployments) can allocate and prioritize resources to minimize the loss of life. The emergency response capabilities can be significantly improved to reduce casualties and facilitate evacuations by permitting rapid and effective deployment of emergency operations. To increase its effectiveness, the Rapid Response data should possibly be linked with the incident command and emergency management systems.

Ground motion data related with power transmission facilities, gas and oil lines and transportation systems (especially fast trains) allow for rapid assessment of possible damages to avoid secondary risks. Water, wastewater and gas utilities can locate the sites of possible leakage of hazardous materials and broken pipes. The prevention of gas-related damage in the event of an earthquake requires understanding of damage to pipeline networks and prompt shut-off of gas supply in regions of serious damage.

Available near real time loss estimation tools can be classified under two main categories depending on the size of area they cover: (1) Global/Regional Systems and (2) Local Systems.

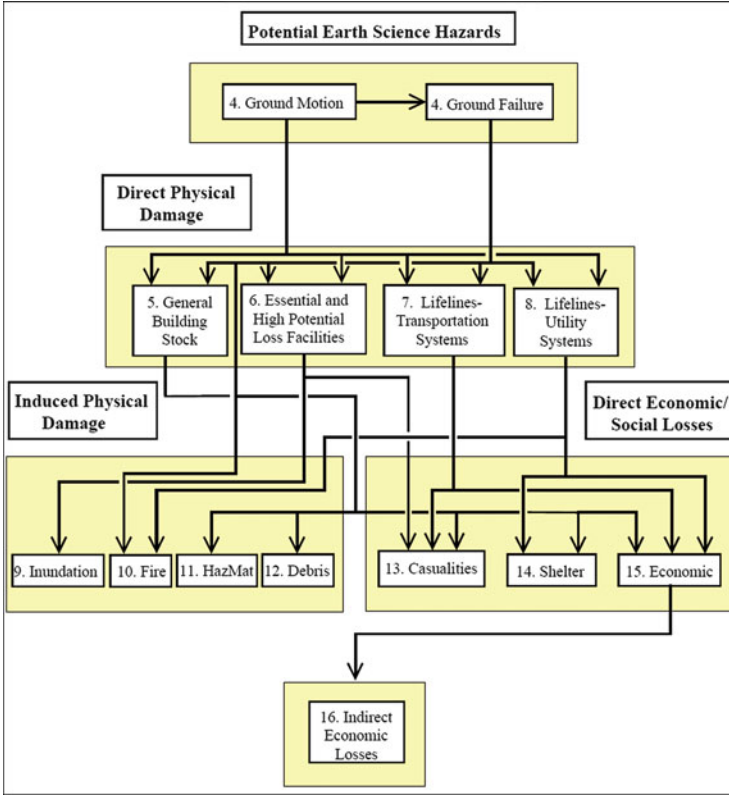
For the global or regional near real time loss estimation efforts, Global Disaster Alert and Coordination System (**GDACS**, <http://www.gdacs.org>), World Agency of Planetary Monitoring Earthquake Risk Reduction (**QLARM**, <http://qlarm.ethz.ch>), Prompt Assessment of Global Earthquakes for Response (**PAGER**, <http://earthquake.usgs.gov/earthquakes/pager>) and NERIES-ELER ([http://www.koeri.boun.edu.tr/Haberler/NERIES%20ELER%20V3.1\\_6\\_176.depnuh](http://www.koeri.boun.edu.tr/Haberler/NERIES%20ELER%20V3.1_6_176.depnuh)) can be listed.

Several local systems capable of computing damage and casualties in near real time already exist in several cities of the world such as Yokohama, Tokyo, Istanbul, Taiwan, Bucharest and Naples (Erdik et al. 2011).

## 2.2 Earthquake Loss Estimation Methodology

An extensive body of research, tools and applications exists that deals with all aspects of loss estimation methodologies. The components of rapid earthquake loss estimation will be addressed following the structures of the HAZUS-MH (2003) and the OpenQuake (Silva et al. 2013) earthquake loss assessment model. Both of these developments use comprehensive and rigorous loss assessment methodologies that can only be adapted to rapid earthquake loss assessment after intelligent simplifications.

The HAZUS-MH Earthquake Model (HAZUS-MH 2003) is developed to provide a nationally applicable methodology for loss estimates of damage and loss to buildings, essential facilities, transportation and utility lifelines, and population based on scenario or probabilistic earthquakes. HAZUS first discusses the inventory data including the Collection and Classification schemes of different systems, attributes required to perform damage and loss estimation, and the data supplied with the methodology. The loss assessment methodology that HAZUS uses consists of the main components of: Potential Earth Science Hazard, Direct Physical



**Fig. 2.2** Flowchart of the HAZUS earthquake loss estimation methodology

Damage, Induced Physical Damage and Direct Economic/Social Loss, as illustrated in the flowchart provided in Fig. 2.2. As indicated by arrows on the flowchart, modules are interdependent with output of some modules acting as input to others.

The main ingredients of the HAZUS loss assessment methodology are as follows.

- **Potential Earth Science Hazards:** Potential earth science hazards include ground motion, ground failure (i.e., liquefaction, landslide and surface fault rupture) and tsunami/seiche.
- **Direct Physical Damage:** Encompasses the modules for General Building Stock, Essential and High Potential Loss Facilities, Lifelines – Transportation and Utility Systems. The General Building Stock module determines the probability of Slight, Moderate, Extensive and Complete damage to general building stock through the use of fragility curves, that describe the probability of reaching or exceeding different states of damage given peak building response, and the building capacity (push-over) curves, that are used (with damping-modified demand spectra) to determine peak building response

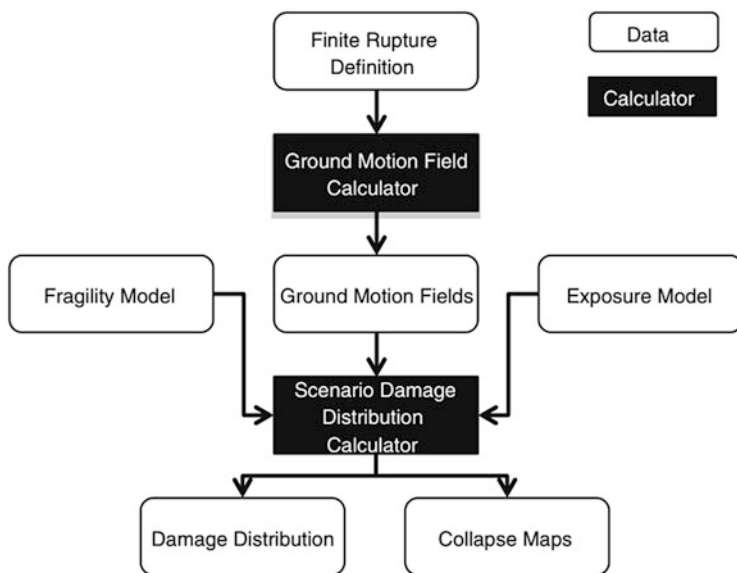
- **Induced Physical Damage:** This module models the damage caused by Inundation, Fires Following Earthquakes, Hazardous Materials Release and Debris.
- **Direct Economic/Social Losses:** Casualties, Shelter Needs and Economic Loss models are encompassed under this component. The Casualty module describes and develops the methodology for the estimation of casualties, describes the form of output, and defines the required input. The methodology is based on the assumption that there is a strong correlation between building damage (both structural and nonstructural) and the number and severity of casualties. The module for Direct Economic Losses describes the conversion of damage state information into estimates of economic loss. The methodology provides estimates of the structural and nonstructural repair costs caused by building damage and the associated loss of building contents and business inventory. The Indirect Economic Losses are also treated as an extension of this module.

A recent development on earthquake loss estimation based on comprehensive methodologies is the OpenQuake project (<http://www.globalquakemodel.org/openquake/>) which has been initiated as part of the global collaborative effort entitled Global Earthquake Model (GEM) (<http://www.globalquakemodel.org>). OpenQuake is a web-based risk assessment platform, which offers an integrated environment for modeling, viewing, exploring and managing earthquake risk (Silva et al. 2013). The engine behind the platform currently has five main calculators (Scenario Risk, Scenario Damage Assessment, Probabilistic Event Based Risk, Classical PSHA-based Risk and Benefit-Cost Ratio). The Scenario Damage Assessment calculator uses a rigorous methodology in estimating damage distribution due to a single, scenario earthquake, for a spatially distributed building portfolio, which can be used for post-earthquake loss assessment. Workflow of the Scenario Damage Assessment is provided in Fig. 2.3, after Silva et al. (2013).

In this methodology, a finite rupture definition of the earthquake needs to be provided, along with the selected GMPE. A set of ground-motion fields is computed, with the possibility of considering the spatial correlation of the ground-motion residuals. Then, the percentage of buildings in each damage state is calculated for each asset the fraction of buildings in each damage state using the fragility models. By repeating this process for each ground-motion field, a list of fractions (one per damage state) for each asset is obtained to yield the mean and standard deviation of this list of fractions for each asset. The absolute building damage distribution is obtained by multiplying the number or area of buildings by the respective fractions with confidence intervals (Crowley and Silva 2013).

The key ingredients of the OpenQuake scenario risk assessment methodology are as follows.

- **Rupture model (Finite Rupture Definition):** The definition of the finite rupture model, specified by a magnitude and a rupture surface geometry, is a key input for scenario risk and damage analysis. The rupture surface geometry can be as simple as the hypocenter point or complex, described by the rake angle and other fault geometrical surface attributes, depending on the level of knowledge.
- **Fragility model:** Fragility is defined as the probability of exceeding a set of limit states, given a range of intensity measure levels. A fragility model can either be



**Fig. 2.3** Workflow of scenario risk assessment

defined as: discrete fragility models, where a list of probabilities of exceedance per limit state are provided for a set of intensity measure levels, or as continuous fragility models, where each limit state curve is modeled as a cumulative lognormal function, represented by a mean and standard deviation.

- **Exposure Model:** The exposure model contains the information regarding on the assets (physical elements of value) exposed to the earthquake hazard within the region of interest. A number of attributes (such as: construction type/material, height, age and value) are required to define the characteristics of each asset. Building taxonomy (classification scheme) and the geographic location respectively allows for the association of the asset with the appropriate fragility function and the site-specific seismic hazard.

The important ingredients of both of these earthquake loss estimation methodologies, in consideration of the “rapid” assessment of earthquake losses, are Ground Motion, Direct Physical Damage to General Building Stock and as Direct Economic/Social (Casualties) Losses.

### 2.2.1 Ground Motion

Bird and Bommer (2004) has shown that 88 % of damage in recent earthquakes has been caused by ground shaking, rather than secondary effects (e.g. ground failures, tsunamis). As such the quantification of the vibratory effects of the earthquakes is of prime importance in rapid loss assessments.

Almost all deterministic earthquake loss assessment schemes rely on the quantification of the earthquake shaking as intensity measure parameters in geographic gridded formats. The earthquake shaking can be determined theoretically for assumed (scenario) earthquake source parameters through ground motion prediction relationships GMPE's (i.e. attenuation relationships) or using a hybrid methodology that corrects the analytical data with empirical observations, after an earthquake. Either procedure yields the so-called, maps that display the spatial variation of the peak ground motion parameters or intensity measures. We owe this "ShakeMap" term to the USGS program that provides near-real-time maps of ground motion and shaking intensity following significant earthquakes in the United States as well as around the Globe (<http://earthquake.usgs.gov/eqcenter/shakemap/>). ShakeMap uses instrumental recordings of ground motions, kriging techniques and empirical ground motion functions to generate an approximately continuous representation of the shaking intensity shortly after the occurrence of an earthquake (Wald et al. 2005). In this connection Harmandar et al. (2012) has developed a novel method for spatial estimation of peak ground acceleration in dense arrays. The presented methodology estimates PGA at an arbitrary set of closely spaced points, in a way that is statistically compatible with known or prescribed PGA at other locations. The observed data recorded by strong motion stations of Istanbul Earthquake Rapid Response System are used for the development and validation of the new numerical method.

The data that are generated via ShakeMap can be used as inputs for the casualty and damage assessment routines for rapid earthquake loss estimation. In USA, and increasingly in other countries, these maps are used for post-earthquake response and recovery, public and scientific information, as well as for loss assessment and disaster planning.

Needless to say, for rapid loss assessment after an earthquake the fast and reliable information on the source location and magnitude is essential. Most rapid loss basements (e.g. PAGER and QLARM) rely on teleseismic determinations of epicenters. This reliance can create error in loss estimations, especially in populated areas, since the mean errors in real-time teleseismic epicenter solutions, provided by U.S. Geological Survey (USGS, the PDE) and/or the European Mediterranean Seismological Center (EMSC), can be as large as 25–35 km (Wyss et al. 2011).

Real-time seismology has made significant improvements in recent years, with source parameters now available within short time after an earthquake. In this context, together with the development of new ground motion predictive equations (GMPEs) that are able to account for source complexity, the generation of strong ground motion shaking maps in quasi-real time has become ever more feasible after the occurrence of a damaging earthquake (Spagnuolo et al. 2013).

The increased availability of seismic intensity data (such as those from "Did You Feel It-DYFI" type programs) immediately following significant earthquakes offers the opportunity to supplement instrumental data for the rapid generation of ShakeMaps. With minor filtering and with sufficient numbers, the intensity data reported through DYFI were found to be a remarkably consistent and reliable measure of earthquake effects (e.g., Atkinson and Wald 2007).

### 2.2.2 *Direct Physical Damage to Building Stock*

For the assessment of direct physical damages, general building stock inventory data and the associated fragility relationships are needed.

#### 2.2.2.1 **Inventory**

To perform a seismic loss assessment, an inventory of the elements at risk should be defined. The classification systems used to define the inventories, the necessary inputs for each level of analysis and the default databases should be compatible with the fragility relationships. The definition of a classification system for the characterization of the exposed building stock and the description of its damage is an essential step in a risk analysis in order to ensure a uniform interpretation of data and results. For a general building stock the following parameters affect the damage and loss characteristics: structural (system, height, and building practices), nonstructural elements and occupancy (such as residential, commercial, and governmental). Building taxonomies define structure categories by various combinations of use, time of construction, construction material, lateral force-resisting system, height, applicable building code, and quality (HAZUS-MH 2003; EMS-98-Grünthal 1998; RISK-UE 2001–2004). The inter-regional difference in building architecture and construction practices should be reflected in building classifications for the development of inventories and fragility information. Only limited number of countries and cities has well developed building inventories. Several efforts are underway, such as PAGER and Global Earthquake Model-GEM ([www.globalquakemodel.org](http://www.globalquakemodel.org)) projects, to develop global building inventory databases.

Publicly available data includes: UN-Housing database, UN-HABITAT, UN Statistical database on Global Housing (1993) housing censuses, Population and Housing Censuses of individual countries (United Nations 2005), the World Housing Encyclopedia (WHE) database developed by EERI (2007).

In order to quantify earthquake risk of any selected region or a country of the world within the Global Earthquake Model (GEM) framework ([www.globalquakemodel.org/](http://www.globalquakemodel.org/)), a systematic compilation of building inventory and population exposure is indispensable. Through the consortium of leading institutions and by engaging the domain-experts from multiple countries, the GED4GEM project has been working towards the development of a first comprehensive publicly available Global Exposure Database (Gamba et al. 2012).

ELER software (Sect. 2.4.4 of this chapter) uses a proxy procedure that relies on land use cover and population distributions to develop regional scale building inventories (Demircioglu et al. 2009).



### 2.2.2.2 Fragility Functions

A seismic fragility function defines loss (here, probability of buildings in various damage states as a result of direct physical damage) as a function of shaking intensity measure. The fragility functions can be classified under three main groups: Empirical (damage probability matrices or vulnerability functions based on field surveys, typology or expert judgement), Analytical (using capacity spectrum or other non-linear static procedures, collapse mechanism-based or displacement-based methods) or Hybrid.

The statistical method for the development of structural fragility functions is empirical that is, it employs loss data from historical earthquakes. The observed damage at various locations can be correlated to instrumental ground motion, intensity or some measure of intensity (Spence et al. 1992). Statistically derived building damage probability matrices (DPM) were first proposed by Whitman et al. (1973). The DPMs developed in the ATC-13 (1985) use expert opinion. He essentially partitioned the observed damage data from the 1971 San Fernando earthquake using various structural classes (taxonomy) and damage state categories as a function of the ground motion intensity (MMI). The statistical (or observed) methods are of greater relevance with non-engineered buildings where substantial damage data is available. The statistical approach offers conceptual simplicity and confidence since it is based on empirical loss data. However, the averaging effect of the definition of the intensity between different building types and damage states sets a limit to their applications. Using the EMS'98 (Grünthal 1998) intensity definitions, Giovinazzi and Lagomarsino (2004) developed a method on the basis of beta damage distribution and fuzzy set theory to produce DPM's. This method has been incorporated into the ESCENARIS and ELER earthquake loss assessment tools (Sect. 2.3). Empirical vulnerability curves (Rossetto and Elnashai 2003) and PSI-via-MSK (Spence et al. 1991) are developed to give a continuous function of intensity versus damage.

Analytical (or predicted) fragility refers to the assessment of expected performance of buildings based on calculation and building characteristics, or on judgment based on the "expert's" experience. The fragility relationships refer to the structural damage states defined (essentially on the basis of displacement drifts) as Slight, Moderate, Extensive and Complete. Each fragility curve is associated with a standard deviation that encompasses the uncertainties stemming from damage threshold, capacity spectrum and the seismic demand.

An analytical method for estimating seismic fragility that uses nonlinear pseudo-static structural analysis is described by Kircher et al. (1997), where the lateral force versus the lateral displacement curve of the building structure, idealized as an equivalent nonlinear, single degree of freedom (SDOF) system, is obtained. This curve is transformed to the spectral displacement-spectral acceleration space to obtain the so-called capacity spectrum. Building capacity spectra vary between different buildings reflecting structural types, local construction practices and building code regulations.

The analytical fragility procedure, commonly called the Capacity Spectrum Method, essentially involves the comparison of the capacity of a structure, represented by the capacity spectrum, with the seismic demand represented by an acceleration displacement response spectrum (ADRS – Mahaney et al. 1993). The “performance point” of a model building type is obtained from the intersection of the capacity spectrum and the demand spectrum and this is then input into fragility curves which allow the probability of exceeding a number of damage states, given this performance point.

The capacity spectrum method, originally derived by Freeman (1998), is first implemented within the HAZUS procedure (FEMA 1999, 2003) as well as in many other earthquake loss estimation analyses: HAZ-Taiwan (Yeh et al. 2000, 2006), Risk-UE (Mouroux et al. 2004; Mouroux and Le Brun 2006), EQRM (Robinson et al. 2005), SELENA (Molina and Lindholm 2005 and ELER (Erdik et al. 2008, 2010; Hancılar et al. 2010).

DBELA (Displacement-Based Earthquake Loss Assessment) method (Crowley et al. 2004; Bal et al. 2008a) relies on the principles of direct displacement-based design method of Priestley (1997, 2003). DBELA method compares the displacement capacities of the substitute SDOF models of the buildings are compared with the seismic demand at their effective periods of vibration at different levels of damage. Buildings are classified on the basis of their response mechanisms: beam-sway or column-sway and the displacement capacities and periods of vibration for each damage state computed. Structural displacements are used to define the limit states of damage.

### ***2.2.3 Casualties as Direct Social Losses***

One of main reasons for rapid earthquake loss estimation is to estimate the spatial distribution of casualties, such that the search and rescue (SAR) and other emergency response activities can be prioritized and rationally coordinated. Casualty estimations encompass significant uncertainties since the casualty numbers vary greatly from one earthquake to another and they are poorly documented.

Apart from simple correlations with intensity or magnitude and population density, the casualty numbers are generally estimated via a correlation with the damage state experienced by a structure, the time of day, the structural use, and other factors. ATC-13 (1985) casualty estimation model consists of tabulated injury and death rates related to a building’s level of damage, or damage state, providing a 4:1 ratio of serious injuries to deaths, and 30:1 ratio of minor injuries to deaths. The model does not provide any differentiation of structural types, suggesting only taking 10 % of the rates for light steel and wood-frame structures.

The casualty estimation model of Coburn and Spence (2002) is based on the distribution of buildings in the complete damage state (D5) as defined in EMS’98. The number of deaths is obtained by multiplication of D5, average people in each collapsed building, percentage of occupants at time of shaking, expected trapped

occupants, mortality at collapse and mortality post-collapse. However, it is not in event tree format and does not account for non collapse (damage) related casualties, nor does it account for the population not indoors at the time of earthquake. Coburn and Spence (2002) notes that especially for cases of moderate levels of damage, i.e. those where fewer than 5000 buildings were damaged, the casualty estimations could be highly inaccurate. Irrespective of the methodology chosen, casualty numbers are computed for three different day time scenarios (night time, day time, and commuting time). This methodology was then improved through the LessLoss methodology of Spence (2007a) with other damage states also taken into account in terms of fatalities. In addition, updated casualty and injury ratios were produced based on a greater set of earthquakes. So and Spence (2009) explored further the relationship of building.

HAZUS-MH (2003) model estimates casualties directly caused by structural or nonstructural damage under four severity levels to categorize injuries, ranging from light injuries (Severity Level 1) to death (Severity Level 4). The model provides casualty rates for different structural types and damage states. Relevant issues in casualty estimation such as occupancy potential, collapse and non-collapse vulnerability of the building stock, time of the earthquake occurrence, and spatial distribution of the damage, are included in the methodology. Casualties caused by a postulated earthquake can be modeled by developing a tree of events leading to their occurrence.

Recent empirical methods of Porter et al. (2008a, b), Jaiswal et al. (2009) and Jaiswal and Wald (2010c) have concentrated on the key parameters of intensity as the hazard metric versus fatality to population ratios or the death rate in collapsed buildings, using expert opinion related collapse ratios and historical data. The earthquake fatality rate is defined as total killed divided by total population exposed at specific shaking intensity level. The total fatalities for a given earthquake are estimated by multiplying the number of people exposed at each shaking intensity level by the fatality rates for that level and then summing them at all relevant shaking intensities. The fatality rate is expressed in terms of a two-parameter lognormal cumulative distribution function of shaking intensity. The parameters are obtained for each country or a region by minimizing the residual error in hindcasting the total shaking-related deaths from earthquakes recorded between 1973 and 2007. A new global regionalization scheme is used to combine the fatality data across different countries with similar vulnerability traits.

The study of the socio-economic losses associated with past earthquakes has gained a new dimension with the development of the worldwide catalogue of damaging earthquakes and secondary effects database (CATDAT) (Daniell et al. 2011c, 2012b). CATDAT has been created using over 20,000 information sources to present loss data from 12000+ historical damaging earthquakes since 1900, with 7000+ examined and validated before insertion into the database. In addition to seismological information, each earthquake includes parameters on building damage data and socio-economic losses. CATDAT have facilitated the study of socio-economic earthquake losses and the derivation of associated fragility/vulnerability relationships. Daniell (2014) has developed an approach to rapidly

calculate fatalities and economic losses from earthquakes using the input of intensity based map and historical earthquakes as a proxy over multiple temporal and spatial scales. The population and its social and economic status for each earthquake were compared to the detailed socio-economic data in CATDAT to produce the functions. Temporal relationships of socio-economic losses were explored in order to calibrate loss functions.

### ***2.2.4 Estimation of Economic Losses***

Financial loss is, essentially, the translation of physical damage into total monetary loss using local estimates of repair and reconstruction costs. Studies on economic impacts of earthquakes have been usually examined in two categories: (a) loss caused by damage to built environment (direct loss), and (b) loss caused by interruption of economic activities (indirect loss). Simple economic loss models are based on direct calculation of property values multiplied by some form of damage metric.

HAZUS-MH (2003) estimates losses at three levels of accuracy: Levels 1, 2, and 3.

Level 1: A rough estimate based solely on data from national databases (demographic data, building stock estimates, national transportation and infrastructure data) included in the HAZUS-MH software distribution.

Level 2: A more accurate estimate based on professional judgment and detailed information on demographic data, buildings and other infrastructure at the local level.

Level 3: The most accurate estimate based on detailed engineering input that develops into a customized methodology designed to the specific conditions of a community.

The level of accuracy encompassed in “Level 1” can be suitable for post-earthquake rapid economic loss assessment.

Through use of statistical regression techniques, data from past earthquakes can be used to develop relationships (Loss Functions) for predicting economic losses. However the existing economic loss data are scarce, biased for heavy damage and could also be proprietary. Loss functions can be estimated by using analytical procedures in connection with a Monte Carlo simulation technique. However, such procedures are not intended for rapid loss estimation type applications.

Losses are generally calibrated to damage states in order to determine direct losses. The definition of the slight, moderate and heavy damage classes in terms of losses has a large variation in terms of potential loss estimates. Let alone the rapid assessment, even the formal quantification of economic losses is a very challenging issue. The technical manual of HAZUS-MH states that the total uncertainty (including that of the ground shaking) is “possibly at best a factor of two or more”.

Chan et al. (1998) have proposed a quick and approximate estimation of earthquake loss using with detailed local GDP and population data, instead of the

detailed building inventory required in traditional loss estimation methodologies. This method has been used for numerous case studies. Their method combines seismic hazard, GDP, population data, published earthquake loss data, and the relationship between GDP and known seismic loss, to estimate earthquake loss from the following relationship:

$$L = \Sigma P(I) \times F(I, GDP) \times GDP \quad (2.1)$$

where  $L$  is the economic loss,  $P(I)$  is the probability of an earthquake of intensity  $I$ , and  $F(I, GDP)$  is a measure of the area's fragility to earthquake damage for the given GDP value and the earthquake of intensity  $I$ . The GDP is used as a macroeconomic indicator to represent the total exposure of an area in the earthquake loss estimation. In this study  $F(I, GDP)$  is determined from the relationship between reported losses from earthquakes to the computed GDP of the affected area. Since GDP is usually provided for a country, it must be apportioned over the nation to the affected area. For this purpose Chan et al. (1998) relies on the correlation between GDP and population density.

The estimates of the direct economic losses due to building damage, which consist of capital stock loss, are relatively easier to be included in rapid loss assessments. These losses are generally quantified as Loss Ratios (LR) – the loss as a percentage of the building replacement value. The economic losses to other elements of the built environment and indirect economic losses, representing the losses due to various forms of post-earthquake socioeconomic disruptions (such as employment and income, insurance and financial aids, construction, production and import-export of goods and services) cannot be rationally included in rapid earthquake loss assessment estimations.

Jaiswal and Wald (2011, 2013) have developed a model of economic losses based on economic exposure versus intensity correlations to rapidly estimate economic losses after significant earthquakes worldwide. The requisite model inputs are shaking intensity estimates made by the ShakeMap system, the spatial distribution of population available from the LandScan database, modern and historic country or sub-country population and Gross Domestic Product (GDP) data, and economic loss data from Munich Re's historical earthquakes catalog. Earthquakes from 1980 to 2007 were examined using economic loss estimates from past events from the MunichRe NatCat Service database. The methodology uses a wealth index as a proxy for exposure, multiplying this in much the same way as a multiplier-output ratio has been applied in Chen et al. (1997a). The process consists of using a country specific multiplicative factor to accommodate the disparity between economic exposure and the annual per capita GDP, and it has proven successful in hindcasting past losses. Although loss, population, shaking estimates, and economic data used in the calibration process are uncertain, approximate ranges of losses can be estimated for the primary purpose of gauging the overall scope of the disaster and coordinating response. The proposed methodology is both indirect and approximate and is thus best suited as a rapid loss estimation model for applications.

Daniell et al. (2012a) has analysed the trends in economic losses (direct, indirect and insured) in earthquakes since 1900 using CATDAT Damaging Earthquakes Database and developed methodologies for the rapid assessment of economic losses (Daniell 2014). In order to compare the economic losses of the historic earthquakes, the losses were converted into today's dollars.

### ***2.2.5 Uncertainties in Loss Estimation***

Uncertainties are inherent in any loss estimation methodology. They arise in part from incomplete scientific knowledge concerning earthquakes, earthquake ground motion and their effects upon buildings and facilities. They also result from the approximations and simplifications that are necessary for comprehensive analyses. Incomplete or inaccurate inventories of the built environment, demographics and economic parameters add to the uncertainty. These factors can result in a range of uncertainty in loss estimates produced by the HAZUS-MH Earthquake Model, possibly, at best, a factor of two or more. HAZUS-MH (2003).

The earthquake loss estimations should consider the uncertainties in seismic hazard analyses, and in the fragility relationship. There exists considerable amount of epistemic uncertainty and aleatory variability in ShakeMaps. Accuracy of the ShakeMap is mainly related to two factors: (1) the proximity of a ground motion observation location, i.e. the density of the strong ground motion network in the affected area, and (2) the uncertainty of estimating ground motions from the GMPE, most notably, elevated uncertainty due to initial, and unconstrained source rupture geometry. The epistemic uncertainties become highest for larger magnitude events when rupture parameters are not yet well constrained (Wald et al. 2008). Aleatory uncertainties may be reduced if the bias correction with recorded amplitudes is performed directly on the ground surface rather than at bedrock level which is the case in the current ShakeMap application (USGS, ShakeMap).

The reliability of the fragility relationships is related to the conformity of the ground motion intensity measure with the earthquake performance (damage) of the building inventory. Estimates of human casualties are derived by uncertain relationships from already uncertain building loss estimates, so the uncertainties in these estimates are compounded (Coburn and Spence 2002).

It is possible to examine the effect of cumulative uncertainties in loss estimates using discrete event simulation (or Monte-Carlo) techniques if the hazard and that the probability distribution of each of the constituent relationships is known. The general finding of the studies on the uncertainties in earthquake loss estimation is that the uncertainties are large and at least as equal to uncertainties in hazard analyses (Stafford et al. 2007).

## 2.3 Earthquake Loss Estimation Software Tools

For known inventories of buildings and under conditions where the earthquake hazard in terms of ground shaking distribution can be assessed rapidly after an earthquake, these tools can be adapted for rapid loss estimation. Daniell (2009, 2011b) has provided a comprehensive comparison between different earthquake loss estimation software packages, in terms of their applicability regions, exposure resolution (district, city, regional, country), hazard (deterministic predicted, deterministic observed, probabilistic), vulnerability type (analytical, empirical, socio-economic). Strasser et al. (2008) has provided a comparison of five selected European earthquake loss estimation software packages (KOERILOSS-ELER, SELENA, ESCENARIS, SIGE-DPC and DBELA), using Istanbul as a test bed. The packages considered common inputs in terms of ground motions, building inventory and population; however the fragility functions and modelling assumptions differed in each package. The overall estimates of building damage were close to each other. However, the results often substantially differed at grid cell level. In terms of social losses, the predictions from the various approaches show a large degree of scatter, mostly driven by differences in the casualty rates assumed.

A brief description and references for the selected earthquake loss assessment software can be given as follows:

### 2.3.1 HAZUS

HAZUS-MH (FEMA and NIBS 2003) is developed by the United States Federal Emergency Management Agency (FEMA) for the prediction and mitigation of losses due to earthquakes (HAZUS), hurricanes and floods (Whitman et al. 1997; Kircher et al. 2006). The package is intended for U.S. applications only and includes federally collected data as default. The inventory is classed based on 36 different types of building based on construction standards and material as well as size and building use. HAZUS-MH MR2 version, released in 2006, includes the capability for rapid post-event loss assessment.

### 2.3.2 EPEDAT

The EPEDAT (Early Post-Earthquake Damage Assessment Tool) is designed by EQE International, Inc. for post-earthquake loss estimation (Eguchi et al. 1997). The output encompasses damage (building and lifelines) and casualty for California based on county specific housing and demographic data. It is Windows-based and uses Modified Mercalli Intensity to quantify the hazard.

### **2.3.3 SIGE**

SIGE, developed by Italian National Seismic Service of the Civil Protection Department, is used for rapid approximate estimate of the damage (Di Pasquale et al. 2004). The first update of the program (FACES) considers linear sources, directivity effects, and the influence of focal depth. The most recent modification of the codes has been implemented in a new model called ESPAS (Earthquake Scenario Probabilistic Assessment).

### **2.3.4 KOERILOSS**

A scenario-based building loss and casualty estimation model developed by Bogazici University (Erdik and Aydinoglu 2002; Erdik et al. 2003a, b; Erdik and Fahjan 2006) for estimating earthquake losses in Istanbul, Izmir, Bishkek and Tashkent. Derivatives of the model were used in the EU FP5 LessLoss project as well as for the assessment of scenario earthquake losses in Amman. The methodology considers both deterministic (scenario) and probabilistic forecasting approaches. The fragility calculations can be based on empirical results (EMS intensity-based) or on a response-spectrum-based method similar to HAZUS. It is used for rapid loss assessment in connection with the Istanbul Earthquake Rapid Response System, described in Sect. 2.5.3 of this chapter.

### **2.3.5 ESCENARIS**

ESCENARIS (Roca et al. 2006) is the software tool developed for Catalonia. The methodology relies on the use of scenario-based earthquake hazards and intensity-based empirical fragility functions of Giovinazzi (2005). The losses are based on the building stock and classes of social impact.

### **2.3.6 CAPRA**

CAPRA (Central American Probabilistic Risk Assessment – [www.ecapra.org](http://www.ecapra.org)) Project has developed a region-specific Earthquake Loss Estimation model using a Web 2.0 format. It is currently under construction (Anderson 2008).



### **2.3.7 LNECLOSS**

LNECLOSS is a software package developed by the Laboratório Nacional de Engenharia Civil (LNEC) in Lisbon, Portugal (Sousa et al. 2004). LNECloss is an earthquake loss assessment tool, integrated on a Geographic Information System (GIS), which comprises modules to compute seismic scenario bedrock input, local soil effects, fragility and fragility analysis, human and economic losses. LNECloss was applied to Metropolitan Area of Lisbon (Zonno et al. 2009).

### **2.3.8 SELENA**

SELENA (Seismic Loss Estimation Using a Logic Tree Approach) is a software package developed at NORSAR for earthquake building damage assessment (Molina and Lindholm 2005). SELENA uses the capacity-spectrum method (HAZUS methodology, ATC-55-ATC 2005) with a logic tree-based weighting of input parameters that reportedly allows for the computation of confidence intervals. GIS software can be utilized at multiple levels of resolution to display predicted losses graphically. Detailed information on SELENA is provided in Sect. 2.4 of this chapter.

### **2.3.9 DBELA**

DBELA (Displacement-Based Earthquake Loss Assessment) is an earthquake loss estimation tool currently being developed at the ROSE School/EU-Centre in Pavia (Crowley et al. 2004; Calvi et al. 2006; Bal et al. 2008a). The methodology is essentially based on comparison of the displacement capacity of the building stock (grouped by structural type and failure mechanism) and the imposed displacement demand from a given earthquake scenario. The methodology aims to allow a good correlation with damage, ease of calibration to varying building stock characteristics and systematic treatment of all sources of uncertainty. It takes into account the uncertainties associated through the process for demand and capacity. Applications of the methodology were carried out for loss assessment in the Marmara Region (Bommer et al. 2006).

### **2.3.10 EQSIM**

EQSIM (EarthQuake damage SIMulation) is the rapid earthquake damage estimation component of the Disaster Management Tool (DMT) currently being

developed at the University of Karlsruhe (Baur et al. 2001; Markus et al. 2004). The loss estimation methodology is based on the adaptation capacity spectrum method used in HAZUS to reflect the European building practice. EQSIM has been used to assess earthquake losses in Bucharest on the basis of scenario earthquakes (Wenzel and Marmuraenu 2007).

### **2.3.11 *QUAKELOSS***

QUAKELOSS is a computer tool for estimating human loss and building damage due to Earthquakes developed by the staff of the Extreme Situations Research Center in Moscow. An earlier version of this program and data set is called EXTREMUM (Larionov et al. 2000). QUAKELOSS software is used by the World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR) to provide near-real-time estimates of deaths and injuries caused by earthquakes anywhere in the world. The building inventory reportedly incorporates data from about two million settlements throughout the world.

### **2.3.12 *NHEMATIS***

NHEMATIS (Natural Hazards Electronic Map and Assessment Tools Information System) has been developed Emergency Preparedness Canada (Couture et al. 2002). It is a national-scale automated facility for the collection and analysis of natural hazard information combined with characterizations of population and infrastructure to allow analyses of risks. Similar to HAZUS, NHEMATIS integrates an expert system rule base, geographic information system (GIS), relational databases, and quantitative models to permit assessment of the hazard impact.

### **2.3.13 *EQRM***

EarthQuake Risk Management (EQRM), developed by Geoscience Australia, is an event-based tool for earthquake scenario ground motion and scenario loss modeling as well as probabilistic seismic hazard and risk modeling (Robinson et al. 2005, 2006). The risk assessment methodology is based on the HAZUS methodology with some modifications to adapt it to Australian conditions. It has the potential to be used with earthquake monitoring programs to provide automatic loss estimates.

### **2.3.14 OSRE**

The Open Source Risk Engine (OSRE), developed in Kyoto University – Graduate School of Engineering – Department of Urban Management, is multi-hazards open-source software that can estimate the risk (damage) of a particular site (object) given a hazard and the fragility with their associate probability distributions (AGORA-Alliance for Open Risk Analysis, <http://www.risk-agera.org>). The catalogue fragility data for different facility classes was obtained from ATC-13.

### **2.3.15 ELER**

The Joint Research Activity 3 (JRA3) of the EU Project NERIES has developed a methodology and software “Earthquake Loss Estimation Routine – ELER” (ELER V3.1 2010; Erdik et al. 2008, 2010) for rapid estimation of earthquake damages and casualties throughout the Euro-Med Region. ELER is designed as open source software to allow for community based maintenance and further development of the database and earthquake loss estimating procedures. The software provides for the estimation of losses in three levels of analysis. These levels of analysis are designed to commensurate with the quality of the available building inventory and demographic data. Detailed information on ELER is provided in Sect. 2.4 of this chapter.

### **2.3.16 MAEVIZ**

MAEviz, developed in the Mid-America Earthquake Center in University of Illinois, integrates spatial information, data, and visual information to perform seismic risk assessment and analysis ([http://mae.ce.uiuc.edu/software\\_and\\_tools/maeviz.html](http://mae.ce.uiuc.edu/software_and_tools/maeviz.html)). It can perform earthquake risk assessment for buildings (structural and non-structural damage), bridges and gas networks with a built-in library of fragility relationships. In addition to applications in USA and important application of the software has been conducted for the Zeytinburnu District of Istanbul (Elnashai et al. 2007).

## **2.4 Earthquake Rapid Loss Assessment Systems**

Available near real time loss estimation tools can be classified under two main categories depending on the size of area they cover: (1) Global or Regional Systems and (2) Local Systems. For the global or regional near real time loss estimation efforts the following developments will be considered:

- Global Disaster Alert and Coordination System – GDACS (<http://www.gdacs.org>),
- World Agency of Planetary Monitoring Earthquake Risk Reduction – WAPMERR (<http://www.wapmerr.org>),
- Prompt Assessment of Global Earthquakes for Response – PAGER (<http://earthquake.usgs.gov/eqcenter/pager/>),
- Earthquake Loss Estimation Routine – ELER ([http://www.koeri.boun.edu.tr/Haberler/NERIES%20ELER%20V3.1\\_6\\_176.depmuh](http://www.koeri.boun.edu.tr/Haberler/NERIES%20ELER%20V3.1_6_176.depmuh))
- Seismic Loss Estimation using a Logic Tree Approach – SELENA (<http://selena.sourceforge.net/selena.shtml>)

A description of the important rapid earthquake loss assessment systems with global or regional coverage will be provided in the following sub-sections.

### ***2.4.1 PAGER (Prompt Assessment of Global Earthquakes for Response)***

PAGER (Prompt Assessment of Global Earthquakes for Response) is an automated system that produces content concerning the impact of significant earthquakes around the world, informing emergency responders, government and aid agencies, and the media of the scope of the potential disaster. PAGER has three separate methodologies for earthquake loss estimation as part of their package (empirical, semi-empirical and analytical). PAGER rapidly assesses earthquake impacts by comparing the population exposed to each level of shaking intensity with models of economic and fatality losses based on past earthquakes in each country or region of the world (Earle et al. 2009a, b). PAGER products are generated for all earthquakes of magnitude 5.5 and greater globally and for lower magnitudes of about 3.5–4.0 within the US. PAGER's results are posted on the USGS Earthquake Program Web site (<http://earthquake.usgs.gov/>) and sent in near real-time to emergency responders, government agencies, and the media. In the hours following significant earthquakes, as more information becomes available, PAGER's content is modified.

#### **2.4.1.1 Process**

The following steps are used in the PAGER methodology:

1. After the magnitude and hypocenter of an earthquake are determined. The PAGER process begins for each new event with the determination of the earthquake source parameters, macroseismic data and the resulting ShakeMap. For large earthquakes ShakeMaps are further constrained (if available, within several hours) by finite-fault waveform inversions (Wald et al. 2008). The

ShakeMaps are constrained, if available, by measurements from strong-motion seismometers in the region surrounding the ruptured fault. In case ground motion recordings are insufficient, ShakeMaps are constrained using empirical ground motion prediction equations based on magnitude, site amplification, and distance to the fault. Observations reported by people in the shaken region using the USGS “Did You Feel It” system (Wald et al. 1999) are converted to estimates of shaking intensity and also used to constrain the ground motion distribution. ShakeMap generates a soil/rock site-specific ground-motion amplification map based on topographic slope and then converts the estimated ground motions to a map of seismic intensities.

2. Following the determination of the shaking distribution, PAGER takes the grid shaking parameter values produced by ShakeMap and determines the settlements (Geonames, <http://www.geonames.org>) and the population (LandScan) database in each grid cell (accounting for time of day, Jaiswal and Wald 2008a) exposed to each level of Intensity (MMI).
3. Based on the population exposed to each shaking intensity level, the PAGER system estimates total shaking-related losses based on country-specific models developed from economic and casualty data collected from past earthquakes.
4. PAGER’s output is distributed by e-mail and is available on the USGS Earthquake Program webpage (<http://earthquake.usgs.gov/pager/>). The maps and tables in this output provide a quick assessment of the estimated impact of the earthquake. The maps provide an indication of the geographic extent of the shaking and distribution of the affected population. The Earthquake Impact Scale provides alert levels for fatalities and economic losses. These alert levels are based on the range of most likely losses due to earthquake shaking and the uncertainty in the alert level can be gauged by the histogram, depicting the percent likelihood that adjacent alert levels (or fatality/loss ranges) occur. The table included provides information on the impact of an earthquake by providing the total number of people within the map boundary estimated to have experienced each MMI level from I (not felt) to X (extreme) and information on possible building damage at different MMI levels for resistant and vulnerable structures.

#### 2.4.1.2 Building and Population Inventories and Fragilities

EXPO-CAT (<http://earthquake.usgs.gov/research/data/pager/expocat>) provides first-order estimates of the number of people exposed to significant global earthquakes since 1973 using current PAGER methodology (Allen et al. 2009a, b). It combines earthquakes in the Atlas of ShakeMaps (Allen et al. 2008) with a gridded global population database to estimate population exposure at discrete levels of macroseismic intensity. Present-day population exposure is estimated using the Landscan global population database. Combining this population exposure dataset with historical earthquake loss data provided for the calibration loss methodologies against the set of ShakeMap hazard outputs.

Currently a first-order building inventory database compiled from: the housing data of the United Nations (UN 1993) and UN Habitat (2007); data compiled by Population and Housing Censuses of individual countries (UN 2005) and; the World Housing Encyclopedia (WHE) database developed by the Earthquake Engineering Research Institute (EERI 2007) is available (Jaiswal and Wald 2008a, b; Wald et al. 2009a, b). At the country level, the inventory database contains estimates of building types categorized by material, lateral force-resisting system, use, and occupancy characteristics.

In a collaborative effort between the US Geological Survey, the Earthquake Engineering Research Institute, and the [World Housing Encyclopedia](http://www.world-housing.net/) (<http://www.world-housing.net/>), experts from around the world have estimated the distribution of predominant buildings types in each of 26 countries, and provided by judgment or statistical survey collapse fragility functions for the predominant structure types in each country (Jaiswal and Wald 2008b; Porter et al. 2008a, b). Operationally, the current PAGER system relies on the empirically-based loss approach (Wald et al. 2008).

The collapse fragility functions developed for global building types using the procedure described in Jaiswal et al. (2011) is expected to form a starting building damage estimation model within the PAGER semi-empirical vulnerability model.

PAGER's fatality loss models (Wald et al. 2008; Jaiswal and Wald 2010) stems from the wide, global variability in the built environment and uncertainty associated with inventory and structural vulnerability data, as well as the knowledge about past casualties in different countries. The empirical model relies on country-specific earthquake loss data from past earthquakes and makes use of calibrated casualty rates for future prediction. For this purpose, a three tiered approach is adopted for fatality estimation. In the empirical approach, a fatality rate is proposed as a proportion of the population exposed at each intensity level, and depends on the shaking intensity according to a lognormal function, with values of the two separate parameters defining the function, and an uncertainty factor, each for different countries or regions of the world. This empirical approach is mostly adaptable for the developing regions of the world, where the available data does not permit for an analytical analysis to be conducted. The PAGER semi-empirical approach aims to develop a better casualty estimate by using, for the area affected at each intensity level, the number of buildings and their vulnerability to collapse at the estimated ground shaking, combined with an estimate of the fatality (or lethality) rate as a proportion of total occupants, given collapse.

#### 2.4.1.3 Economic Loss Estimation

In order to estimate economic losses an assessment of the economic exposure at various levels of shaking intensity is used. Since the economic value of all the physical assets exposed at different locations in a given area is generally not known and extremely difficult to compile at a global scale, In the absence of such a dataset, the total Gross Domestic Product (GDP) exposed at each shaking intensity is

estimated by multiplying the per-capita GDP of the country by the total population exposed at that shaking intensity level. The total GDP thus estimated at each intensity is then scaled by an exposure correction factor, which represents a multiplying factor to account for the disparity between wealth and/or economic assets to the annual GDP (Jaiswal and Wald 2011).

For this development at least four damaging earthquakes that occurred within a country or region during the observation period between 1973 and 1980. Since only a few countries experienced large, damaging earthquakes for which loss values are available during the observation period, it was necessary to aggregate some countries into regions using the “Human Development Index” (HDI) to estimate the parameters of the economic loss ratio function. The economic exposure obtained using this procedure is a proxy estimate for the economic value of the actual inventory that is exposed to the earthquake.

#### ***2.4.2 GDACS: The Global Disaster Alert and Coordination System***

The Global Disaster Alert and Coordination System – GDACS (<http://www.gdacs.org/>) provides near real-time alerts about natural disasters around the world and tools to facilitate response. GDACS is a joint initiative of the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) and the European Commission that serves to consolidate and improve the dissemination of disaster-related information, in order to improve the coordination of international relief efforts. It started as GDAS, but was later coupled with the coordination information system of the UN Office of Coordination of Humanitarian Affairs-Virtual On-site Operations Coordination Center (the OCHA Virtual OSOCC, <http://vosocc.unocha.org>, <http://vosocc.gdacs.org>). GDACS collects near real-time hazard information and combines this with demographic and socio-economic data to perform a mathematical analysis of the expected impact. This is based on the magnitude of the event and possible risk for the population. The result of this risk analysis is distributed by the GDACS website and alerts are sent via email, fax, and SMS to subscribers in the disaster relief community, and all other persons that are interested in this information.

GDACS collects earthquake information from: United States Geological Survey National Earthquake Information Center (NEIC), European-Mediterranean Seismological Centre (EMSC), GEOFON Program of the GFZ Potsdam and Japan Meteorological Agency (JMA).

Using the reported earthquake parameters, a three level alert based on the LandScan population dataset and the population fragility (European Commission Humanitarian Aid Department Global Needs Assessment Indicator) in the region of interest. Currently, the evaluation of the potential humanitarian impact of earthquakes considers (1) earthquake magnitude, (2) earthquake depth, (3) population

within 100 km of epicenter, and (4) national population fragility. The last two elements are automatically calculated by GIS based on the earthquake epicenter, the LandScan population dataset and ECHO's Global Needs Assessment indicator. The alerts are considered on the basis of the so-called alert score which combines the earthquake magnitude and depth, size of the exposed population and the country-specific fragility index. The alert score is transformed into three alert levels: red, orange and green.

### ***2.4.3 WAPMERR-QLARM World Agency of Planetary Monitoring and Earthquake Risk Reduction***

QLARM (<http://qlarm.ethz.ch>) provides loss estimates for earthquakes in global scale after the event. The post-earthquake alerts issued include number of fatalities and injured, as well as average damage to buildings in the affected settlements. This service is being carried out in partnership between WAPMERR (World Agency of Planetary Monitoring and Earthquake Risk Reduction) and the Swiss Seismological Service (SED-ETH, Zurich). The estimates in the current version include: (1) The expected percentage of buildings in each of five damage states in each settlement, (2) the mean damage state in each settlement, (3) the numbers of fatalities and injured, with error estimates, in each settlement (Trendafiloski et al. 2009b). The loss estimates are reportedly provided in about 30 min after the earthquake.

QLARM is an outgrowth of the former QUAKELOSS software, the computer tool used to estimate the building damage and casualties (Trendafiloski et al. 2009a). Loss estimations are done for the QLARM worldwide database constructed of: (1) point city models for the cases where only summary data for the entire city are available; and, (2) discrete city models where data regarding city sub-divisions (districts) are available (Trendafiloski et al. 2009b). The ground shaking for the settlements is computed based on the magnitude, epicenter and depth of the event using global and regional ground motion prediction models. Soil amplification is estimated using either local data to derive an amplification factor for each discrete city model or global data based on Vs30 values derived from topographic slopes from Allen and Wald (2007).

QLARM calculates the expected building damage using intensity based fragility models, calibrated using about 1,000 earthquakes for which losses are known. Distribution of building stock and population are attributed to these city models. In the data base of QLARM, the population of about two million settlements is known and each settlement has a profile of building fragility. Fragility classes are assigned to different building types considering the fragility table given by the European Macroseismic Scale EMS-98 (Grünthal 1998). Building and population distributions are constructed using the percentage of the number of buildings and population belonging to a particular fragility class. QLARM population database is constructed using national census data and the online sources World Gazetteer and



Geonames. Opinion of local experts, World Housing Encyclopedia and PAGER database are additional sources used to improve the population database. Population distribution by time of the event is taken into account using the model proposed by Coburn and Spence (2002).

The European Macroseismic Method of Giovinazzi (2005) is used to calculate building damages. The fragility models are pertinent to EMS-98 fragility classes and correlate the mean damage grade  $\mu D$  ( $0 \leq \mu D \leq 5$ ) with the seismic intensity and the fragility index.

Human losses are estimated using the casualty event-tree model proposed by Stojanovski and Dong (1994). The probability of occurrence of casualty state for a given seismic intensity is calculated as a product of the damage probabilities for seismic intensity and the casualty probabilities for damage grades of EMS-98. It is claimed that the human losses are estimated within a factor of 2 for past earthquakes.

#### **2.4.4 ELER: Earthquake Loss Estimation**

The Joint Research Activity JRA-3 of the EU Project NERIES aims at establishing rapid estimation of earthquake damages, casualties, shelters and food requirements throughout the Euro-Med Region. Within the scope of this activity, a rapid loss estimation tool (ELER, [http://www.koeri.boun.edu.tr/Haberler/NERIES%20ELER%20V3.1\\_6\\_176.depmuh](http://www.koeri.boun.edu.tr/Haberler/NERIES%20ELER%20V3.1_6_176.depmuh)) is developed by researchers from KOERI, Imperial College, NORSAR and ETH-Zurich. The loss estimation is conducted under three levels of sophistication as elaborated in Fig. 2.4.

The ground motion estimation methodology is common in all levels of analysis. The shake mapping methodology is similar to the USGS Shake Map (Wald et al. 2005). Based on the event parameters the distribution of PGA, PGV, SA ( $T=0.2$  s) and SA ( $T=1$  s) are estimated based on a choice of ground motion prediction models. Local site effects are incorporated either with the Borchardt (1994) methodology or, if available, with the use of Vs30 based amplification functions within the ground motion prediction equations (GMPE). If strong ground motion recordings are also available, the prediction distributions are bias corrected using the peak values obtained from these recordings. Geo-spatial analysis can be also employed in this step, through the Modified Kriging Method. EMS-98 Intensity distributions are obtained based on computed PGA and PGV values using the procedure proposed by Wald et al. (1999). For site-specific analysis, Vs30 values (average shear wave propagation velocity in upper 30 m of the soil medium) are obtained from regional geology (Quaternary, Tertiary, Mesozoic (QTM) maps) or slope-based Vs30 maps (Allen and Wald 2007).

After the estimation of the spatial distribution of selected ground motion parameters, earthquake losses (damage and casualty) can be estimated at different levels of sophistication, namely Level 0, 1 and 2. The differentiation of these levels of

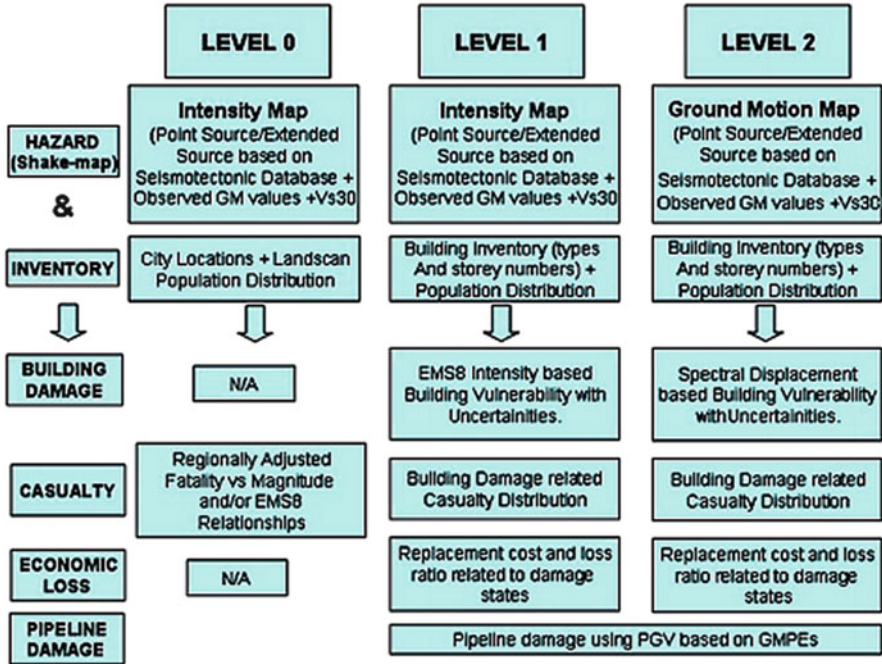


Fig. 2.4 The levels of analysis incorporated in the ELER software

analysis is essentially controlled by the availability of building inventory and demographic data (Demircioglu et al. 2009; ELER v3.1 2010; Erdik et al. 2010).

Both Level 0 (quite similar to PAGER system of USGS) and Level 1 analyses of ELER software are based on obtaining intensity distributions analytically and estimating total number of casualties either using regionally adjusted intensity-casualty or magnitude-casualty correlations (Level 0) or using regional building inventory databases (Level 1). Level 1 type analysis uses EMS98 (Grünthal 1998) based building fragility relationships of Lagomarsino and Giovinazzi (2006) to estimate building damage and casualty distributions.

Level 2 type analysis corresponds to the highest sophistication level in the loss estimation methodology developed. The building damage and casualty distributions are obtained using analytical fragility relationships and building damage related casualty fragility models, respectively. The Level 2 module of ELER aims at assessing the building damage and the consequential casualties using methodologies similar to HAZUS-MH (2003).

#### 2.4.4.1 Demographic and Building Inventory

For all levels of analysis the 30 arc sec (about 1 km) grid based LandScan (Oak Ridge National Laboratory 2011) population data are used. For both the Level 1 and Level 2 analyses options exist for the use of local demographic data for casualty estimation.

ELER is structured in such a way that a building inventory can be classified in terms of any classification system as long as the empirical and/or mechanical fragility relationships associated with each building type is defined by the user. The HAZUS (FEMA 2003), EMS-98 (Grünthal 1998), and RISK-UE (2001–2004) building taxonomies are used as the default main classification systems in the development of ELER. The user has the capability of defining custom fragility curves by “Building Database Creator” tool.

The regional scale building inventory used in Level 1 analysis corresponds to an approximated (proxy) European database consisting of the number of buildings and their geographic distribution. This approximated building database is obtained from CORINE Land Cover (European Environment Agency 1999), LandScan population database and Google Earth (<http://earth.google.com>) and is provided within ELER as the default data for Level 1 analysis. Following the determination governing land cover classes for each country, the basic methodology used in obtaining the country basis proxy distribution of the number of buildings (per unit area in each building class) is as follows (Demircioglu et al. 2009; ELER v3.1 2010; Erdik et al. 2010):

1. Select suitable sample areas from Google Earth for each Corine Land Cover class in all countries
2. Obtain the actual number of buildings in each sample area, automatically using image processing techniques.
3. Approximate the total number of buildings in each country by spreading the sample area building counts to the country
4. Verify (and adjust) the number of buildings thus obtained by computing the population per building for each Corine Land Cover class, and by also checking with the actual number of buildings in a country if such information has been obtained from the corresponding country’s statistical office.

The corresponding RISK-UE building taxonomy classes were identified and the associated percentages have been used to convert the grid based number of buildings to an inventory of differentiated structural types in each country. The grid based distribution of the number of buildings and population thus obtained is aggregated to 30 and 150 s arc grids to form the default data for Level 1 analysis.

#### 2.4.4.2 Building Damage Estimation

Different fragility relationships and building damage assessment methodologies are used under the different levels of analysis.

The Level 0 analysis does not include any building damage assessment. The physical damage in cities and other populated areas can be inferred through the intensities given by the Shakemaps.

For Level 1 damage assessment analysis, the intensity based empirical fragility relationships developed by Lagomarsino and Giovinazzi (2006) are used. ELER software allows for the incorporation of a regional variability factor in these relationships.

Level 2 analysis is essentially intended for earthquake risk assessment (building damage and consequential human casualties) in urban areas (Hancilar et al 2010). As such, the building inventory data for the Level 2 analysis will consist of grid (geo-cell) based urban building (HAZUS or user-defined similar typology) and demographic inventories. The building damage assessment is based on the analytical fragility relationships based on the Capacity Spectrum Method (so-called HAZUS methodology).

For the representation of seismic demand the 5 %-damped elastic response spectrum provided EC8 Spectrum (Eurocode 8, CEN 2003) or IBC 2006 Spectrum (International Building Council 2006) is used. For the estimation of the so-called “Performance Point”, the intersection point of the capacity and the demand curves, ELER uses the procedures based on: the Capacity Spectrum Method specified in ATC-40 (1996), its recently modified and improved version Modified Acceleration-Displacement Response Spectrum Method (FEMA-440) and the Coefficient Method originally incorporated in FEMA-356 (2000). ELER also incorporates another nonlinear static procedure, the so-called “N2 – Reduction Factor Method” method (Fajfar 2000) where the inelastic demand spectra is modified using ductility factor based reduction factors.

#### 2.4.4.3 Casualty Estimation

The casualty estimation is done by using regionally adjusted intensity casualty or magnitude-casualty correlations based on the Landscan population distribution inventory. The module can use previously calculated intensity grid (with the Hazard Module) or a custom intensity grid. There are three possible algorithms for computing the casualty estimation: (a) Samardjieva and Badal (2002), (b) RGELFE (1992), and (c) Vacareanu et al. (2005). The uncertainty regarding the results of this module is substantial, however, it can be a very fast way of providing casualty estimates, based on minimum data that can be easily available.

Casualties in Level 1 analysis is assessed on the basis of the simple correlations with fatalities and the number of buildings damaged beyond repair. The rates of severe injuries were obtained by revising those suggested in ATC-13 (1985) using regional post-earthquake casualty data. The casualty estimation methodology of Coburn and Spence (2002) based on the number of buildings in D5 damage state of EMS98 is also coded in ELER.

The estimation of casualties in Level 2 analysis is the one used in HAZUS based on the number of buildings of a given type at different damaged states and the

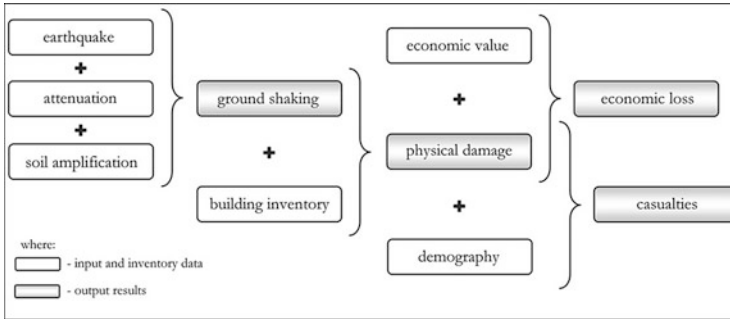
associated casualty rates. The casualty rates corresponding to reinforced concrete and masonry structures given in HAZUS-MH (FEMA 2003) are adopted in ELER. The module computes, after obtaining probabilities for buildings in different damage states (five damage states: slight, moderate, extensive, complete and total collapse), estimates for human casualties, based on HAZUS-MH rates. The output from the module consists of a casualty breakdown by injury severity level, defined by a four level injury severity scale.

#### ***2.4.5 SELENA: Seismic Loss Computation Engine***

SELENA (Seismic Loss Estimation using a Logic Tree Approach) is a software tool for seismic risk and loss assessment (<http://selena.sourceforge.net/selena.shtml>). It relies on the principles of capacity spectrum methods (CSM) and follows the same approach as the loss estimation tool for the United States HAZUS-MH (2003). A logic tree-computation scheme has been implemented in SELENA to account for epistemic uncertainties in the input data. The user has to supply a number of input files that contain the necessary input data (e.g., building inventory data, demographic data, definition of seismic scenario etc.) in a simple pre-defined ASCII format. SELENA computes ground shaking maps for various spectral periods (PGA,  $S_a(0.3\text{ s})$  and  $S_a(1.0\text{ s})$ ), damage probabilities, absolute damage estimates (including Mean Damage Ratios MDR) as well as economic losses and numbers of casualties. Flowchart of a deterministic analysis using SELENA is provided in Fig. 2.5.

In SELENA the provision of seismic demand can be done by assigning PGA or spectral accelerations at 0.3 and 1 s, obtained from seismic hazard assessment, to the geographical units. SELENA can compute the ground motion parameters by built-in GMPRs for deterministic scenario earthquakes. For real time analysis, data from strong motion stations (at least PGA values) can also be used with certain limitations. Based on these ground motion parameters SELENA generates site-specific response spectra based on IBC-2006 (International Code Council 2006), Eurocode 8 (CEN 2003) and Indian seismic building code IS 1893.

SELENA uses analytical approach for obtaining building damage with different user-selectable methodologies: (1) the traditional capacity spectrum method (CSM) as proposed by ATC-40 (ATC 1996), (2) the Modified Acceleration Displacement Response Spectra (MADRS) method according to FEMA 440 (FEMA 2005) and (3) the Improved Displacement Coefficient Method (I-DCM) as given by FEMA 440 (FEMA 2005). Damage probabilities and absolute estimates of structural building damage are computed for the five damage states no, slight, moderate, extensive and complete. The associated economic losses and casualties are estimated on the basis of available building stock inventory, replacement values and demographic information, by adopting the methodology described by HAZUS-MH (2003).



**Fig. 2.5** Principle flowchart of a deterministic analysis using SELENA

The methodology applied in order to estimate the number of human casualties follows basically the HAZUS-MH (2003) approach or the basic approach following Coburn and Spence (2002). For the estimation of economic losses HAZUS-MH (2003) approach is adopted with the possibility to modify the replacement cost percentage.

## 2.5 Local Earthquake Rapid Loss Assessment Systems

Several local systems (country-, city- or, facility-specific) capable of computing damage and casualties in near real time already exist in several regions of the world. For example the Taiwan Earthquake Rapid Reporting System, the Real-time Earthquake Assessment Disaster System in Yokohama (READY), The Real Time Earthquake Disaster Mitigation System of the Tokyo Gas Co. (SUPREME) and the Istanbul Earthquake Rapid Response System (IERRS) provide near-real time damage estimation after major earthquakes (Erdik and Fahjan 2006). Almost all of these systems are based on the assessment of demand in real time from dense strong motion instrument arrays and the estimation of damage on the basis of known inventory of elements exposed to hazard and the related fragility relationships. After an earthquake the shaking and damage distribution maps are automatically generated on the basis of the ground motion intensity measure data received from the field stations, building inventory and the fragility relationships.

### 2.5.1 Earthquake Rapid Reporting System in Taiwan

Earthquake Rapid Reporting and Early Warning Systems in Taiwan, operated by Taiwan Central Weather Bureau, uses a real-time strong-motion accelerograph

network that currently consists of 82 telemetered strong-motion stations distributed across Taiwan, an area of  $100 \text{ km} \times 300 \text{ km}$ . The rapid reporting system can offer information about 1 min after an earthquake occurrence, that includes earthquake location, magnitude and shaking maps (Tsai and Wu 1997; Teng et al. 1997; Wu et al. 1998, 1999, 2004; Shin and Teng 2001; Wu and Teng 2002).

Central Weather Bureau of Taiwan operates two dense digital strong-motion networks: (1) The Taiwan Rapid Earthquake Information Release System (TREIRS), and (2) The Taiwan Strong Motion Instrumentation Program (TSMIP).

TREIRS can obtain earthquake magnitude, epicenter location and focal depth within 90 s after occurrence of earthquakes. The TSMIP system consist of more than 650 stations spaced approximately every 5 km in populated areas in Taiwan. The Early Seismic Loss Estimation (ESLE) module has been developed and integrated with the application software “Taiwan Earthquake Loss Estimation System (TELES) provides decision support soon after occurrence of strong earthquakes for emergency providers (Yeh et al. 2003). TELES software, essentially modeled after HAZUS, acts as a decision support tool in emergency responses. The ESLE module is automatically triggered after receiving earthquake alerts. The estimated damages and casualties are then provided in the form of maps and tables automatically. Currently, the time span to complete the hazard analysis and damage assessment needs 3–5 min depending on the earthquake magnitude, epicenter location and focal depth.

### ***2.5.2 Istanbul Earthquake Rapid Response System***

To assist in the reduction of losses in a disastrous earthquake in Istanbul a dense strong motion network has been implemented. All together this network and its functions is called Istanbul Earthquake Rapid Response and Early Warning System (IERREWS). The system is designed and operated by Bogazici University with the logistical support of the Governorate of Istanbul, First Army Headquarters and Istanbul Metropolitan Municipality (Erdik et al. 2003a, b; Erdik and Fahjan 2006; Şeşetyan et al. 2011). Currently 230 strong motion recorders (including those from the IGDAŞ network) are stationed in dense settlements in the Metropolitan area of Istanbul in on-line mode for Rapid Response information generation. Post-earthquake rapid response information is achieved through fast acquisition, analysis and elaboration of data obtained from these stations.

The Rapid Response part of the IERREWS System satisfies the COSMOS (The Consortium of Organizations for Strong-Motion Observation Systems) Urban Strong-Motion Reference Station Guidelines ([www.cosmos-eq.org](http://www.cosmos-eq.org)) for the location of instruments, instrument specifications and housing specifications. The relative instrument spacing is about 2–3 km which corresponds to about 3 wavelengths in firm ground conditions and more than 10 wavelengths for soft soils for horizontally propagating 1 s shear waves. For communication of data from the rapid response stations to the data processing center and for instrument monitoring a reliable and



redundant GSM 3G communication system (backed up by dedicated landlines and a microwave system) is used.

After an earthquake, the ground motion parameters, spectral displacements at selected periods, are calculated at each station location, are interpolated to determine the spectral displacement values at the center the geo-cells. The earthquake demand at the center of each geo-cell ( $0.005^\circ$  units) is computed through interpolation of these spectral displacements using two-dimensional splines. For the generation of Rapid Response information (Loss Maps) the ELER software is used (Şeşetyan et al. 2011).

The loss estimation relies on the building inventory database, fragility curves and the direct physical damage and casualty assessment techniques. The building inventories (in 24 groups) for each geo-cell together with their spectral displacement curves are incorporated in the software. The casualties are estimated on the basis of the number of occupancies and degree of damage suffered by buildings. The resulting rapid response (i.e. LossMap) information is communicated to the concerned emergency response centers (currently Istanbul Governorate, Istanbul Municipality and First Army Headquarters).

Another application called “SOSEWIN-Self Organizing Seismic Early Warning Information Network”, based on the innovative technology of self-organizing networks, has been set up in the Atakoy region of Istanbul as a prototype (Picozzi et al. 2008). In contrast to centralized conventional Early Warning approach, the SOSEWIN system uses new, low-cost wireless sensing units, specifically designed to form a dense decentralized wireless mesh network (Fleming et al. 2009). The sensors allow the performance of onsite, independent analysis of the ground motion and the real-time communication of estimated parameters. The dedicated algorithms in the system provide the decision to issue warning within the wireless mesh network itself and reduces the lead-time for early warning activities. As a long-term aim of the SOSEWIN system, the use of low-cost sensing nodes by a range of end users including the general public will provide valuable input for higher resolution ShakeMaps with neighborhood-scale loss assessments. In this regard, the increase of SOSEWIN sensing units will complement existing earthquake early warning and rapid response systems.

### ***2.5.3 IGDAS: Istanbul Natural Gas Earthquake Response System***

Istanbul Gas Distribution (IGDAS) is the primary natural gas provider in Istanbul to 5 Million subscribers, and operates an extensive system of 9,867 km of gas lines, with 704 district regulators and 474,000 service boxes.

A real time risk mitigation system, currently encompassing 110 strong motion accelerometers located at critical district regulators, became operational in 2013 (Bıykoğlu et al. 2012). The real-time ground motion data is transmitted to the



IGDAS server at SCADA center and KOERI through 3G. The system works integrated with IERREWS with the total of 230 strong motion stations. The real-time ground shaking maps and grid based pipeline damage maps including pipeline components such as bends, tees, district regulators, isolation joints, valve rooms and service boxes are obtained.

The IGDAS Earthquake Response System follows four stages as below:

1. Real-time ground motion data is transmitted from IGDAS and KOERI stations to the IGDAS Scada Center and KOERI.
2. During an event EW information is sent from IGDAS Scada Center to the IGDAS stations at district regulators.
3. Automatic Shut-Off depending on the threshold level of certain parameters at each IGDAS district regulator is applied, and calculated parameters are sent from stations to the IGDAS Scada Center and KOERI.
4. Integrated ground shaking and damage maps are prepared immediately after the earthquake event.

### ***2.5.4 REaltime Assessment of Earthquake Disaster in Yokohama (READY)***

In 1997 the city of Yokohama installed a dense strong-motion array for earthquake disaster management. The array (called, REal-time Assessment of earthquake Disaster in Yokohama -READY System) consists of 150 strong motion accelerographs at a spacing of about 2 km. In addition borehole strong motion systems at installed at nine different locations for liquefaction monitoring. It is currently used for strong motion monitoring, real-time seismic hazard and risk assessment and damage gathering systems (Midorikawa 2005). These stations are connected to three observation centers, the disaster preparedness office of the city hall, the fire department office of the city and Yokohama City University, by the high-speed and higher-priority telephone lines.

When the accelerograph is triggered by an earthquake, the station computes ground-motion parameters such as the instrumental seismic intensity, peak amplitudes, predominant frequency, total power, duration and response spectral amplitudes. The seismic intensity data is conveyed to the city officials by the pager, and the intensity map of the city is drawn within a few minutes after the earthquake. The map is immediately open to the public through the Internet and local cable TV.

Rapid assessment of the damage to the timber houses is computed and mapped on the basis of their dynamic characteristics and the response spectrum of ground motion. The damage map is displayed with other information such as locations of hospitals, refuges and major roads for emergency transportation (Midorikawa 2004; Ariki et al. 2004).

### 2.5.5 Tokyo Gas: Supreme System

To cope with earthquake related secondary disasters, the new real-time disaster mitigation system for a city gas network has been developed by Tokyo Gas Company. since 1998 for the purpose of realization of dense real-time seismic motion monitoring, quick gas supply shut-off, prompt emergency response and efficient restoration work. In 2001, Tokyo Gas successfully started the operation of SUPREME, which employs 3,800 SI sensors and remote control devices at all the district regulator stations in its service area (3,100 km<sup>2</sup>). In order to avoid earthquake risks due to leakage of gas from breakage of buried pipes, Tokyo Gas Co. Ltd. has developed and put into use a real-time safety control system, called SUPREME ([http://www.tokyo-gas.co.jp/techno/stp3/97c1\\_e.html](http://www.tokyo-gas.co.jp/techno/stp3/97c1_e.html)). The system monitors the earthquake motion at 3,800 district regulators using spectrum intensity sensors, interprets the data, and assesses gas pipe damage in order to decide whether or not the gas supply should be interrupted (Yamazaki et al. 1995; Shimizu et al. 2004 and 2006; Inomata and Norito 2012). Spectrum intensity sensors computes the Housner Intensity (Housner 1961) based on the integral of the 5 % damped response spectra between the periods of 0.1 and 2.5 s.

SUPREME interpolates SI values for 50 m meshes to calculate the number of damaged locations in each mesh in real time, based on SI values observed after disasters and data of geotechnical investigations (local site effects on ground motion) obtained in advance. SUPREME is also equipped with logic to simultaneously estimate the risk of liquefaction and to calculate damaged locations (Inomata and Norito 2012).

## 2.6 Comments and Conclusions

Impact of large earthquakes in urban and critical facilities and infrastructure can be reduced by timely and correct action after a disastrous earthquake. Today's technology permits for the assessments of the distribution of strong ground motion and estimation of building damage and casualties within few minutes after an earthquake.

The reduction of casualties in urban areas immediately following an earthquake can be improved if the location and severity of damages can be rapidly assessed by the information from Rapid Response Systems. The emergency response capabilities can be significantly improved to reduce casualties and facilitate evacuations by permitting rapid, selective and effective deployment of emergency operations.

The ground motion measurement hardware, data transmission systems and the loss assessment methodologies and software needed for the implementation of such Earthquake Rapid Response Systems have reached to a degree of development that can ensure the feasible application of such systems and services throughout the world.

Recent earthquakes provided opportunities for evaluation of the operational rapid loss assessment systems. The Center for Disaster Management and Risk Reduction Technology (CEDIM, [www.cedim.de](http://www.cedim.de)) has critically evaluated rapid loss assessments done after the M7.2 Van Earthquake (Eastern Turkey) of 23 October 2011 in connection with their comprehensive forensic investigations (Wenzel et al. 2012). In Van earthquake event, alerts of major earthquake activity came first from from KOERI, SARBIS, EMSC and USGS. There was much difference in initial hypocenter information from different agencies and the estimates from ELER, PAGER, WAPMERR, CATDAT-EQLIPSE showed a large range of losses. The ELER based rapid loss assessment provided by KOERI proved to be very close to the final losses due to correct location of the earthquake source used (Wenzel et al. 2012; Erdik et al. 2012; CEDIM 2011).

The 2011 Tohoku earthquake is an example that illustrates the importance of post-event analysis. Fifteen alerts were issued by PAGER/ShakeMap in time periods ranging from within 23 min to 6 months after the earthquake. Rapid loss estimations loss estimation for the Tohoku earthquake of 11 March 2011 is compared in Daniell et al. (2011a). It is shown that a number of rapid earthquake loss estimation software packages (PAGER, QLARM, EXTREMUM) have created reasonable estimates of loss in quick time after a disaster. However, the earthquake data alone was not sufficient to produce reliable loss estimates because of the associated tsunami.

Uncertainties in real-time estimates of human losses are a factor of two, at best. And the size of the most serious errors can be an order of magnitude. They can be generated by hypocenter errors, incorrect data on building stock, and magnitude errors, especially for large earthquakes. Several studies have shown that casualty models currently used for rapid post-event casualty estimation involve a high degree of uncertainty. This is essentially due to uncertainty in the earthquake's source parameters and also our lack of knowledge on built environment, its fragility characteristics, and of the survival rates in an earthquake. For example, Spence and So (2011) have compared the performance of WAPMEER and PAGER in the estimation of casualties in several recent earthquakes. They found significant underestimations and overestimations depending on the earthquake. The reduction of the uncertainties inherent in the basic ingredients of earthquake loss assessment is an important issue that needs to be tackled in the future for viability and reliability of rapid loss assessments. Improvement in the speed and quality of moment tensor information, including estimates of rupture direction and fault finiteness, will be needed for refining loss estimates especially in regions without dense local seismograph networks.

Much remains to be done to produce more reliable rapid loss estimates after earthquakes. It is believed that the increasing number of scientific studies, outcomes of the relevant EU projects (such as NERIES, SAFER, NERA and REAKT), ongoing refinements in PAGER methodologies, as well as the expected achievements of the Global Earthquake Model ([www.globalquakemodel.org](http://www.globalquakemodel.org)) project will provide the correct directions and developments in this regard.

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