Geotechnical, Geological and Earthquake Engineering

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SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk

Buildings, Lifelines, Transportation Networks and Critical Facilities

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Preface

Modern societies and economies become more complex and at the same time more sophisticated. Still, the experience from earthquakes reveals that even the developed societies are quite vulnerable, although the provisions against seismic hazards have been considerably improved. Their exposure to seismic risk in prone seismic areas rely on an *integrated seismic risk approach*, which should define accurately the physical seismic risk and the socio-economic vulnerability and resilience. *Physical seismic risk* is defined with the probability of damages and loss to structures and people due to an earthquake of any intensity. *Socio-economic vulnerability* is the expected impact of a given earthquake on the society and the economy. *Resilience* is the capacity of a society and economy to cope with earthquake events. The physical risk assessment depends on the *seismic hazard*, which expresses the probability of ground shaking and induced phenomena i.e. liquefaction, fault crossing, landslides due to earthquakes, the *exposure* of the different assets and the *physical vulnerability* of the exposed elements at risk, which is the vulnerability of structures, their occupants and services to seismic hazard.

A critical component of this chain of seismic risk assessment is the definition and evaluation of the so-called *fragility functions* or *fragility curves*. They provide the necessary link between seismic hazard assessment at a site and the corresponding effects on any kind of exposed structures i.e. buildings, infrastructures, utilities, lifelines and industrial facilities. The majority of currently available approaches to assess the potential losses for a wide group of exposed elements rely on the availability of relevant fragility curves. In the past decades, the field of seismic risk assessment has witnessed remarkable developments.

SYNER-G is a research project funded by European Commission in the frame of FP7 Theme 6: Environment. The objective of SYNER-G is to develop an integrated methodology and the necessary tools for the systemic seismic vulnerability and risk analysis of complex systems exposed to earthquake hazard, like buildings, and aggregates in urban scale, lifelines, transportation and utility networks, gas and electric power systems, critical facilities, and infrastructures. Interactions between different components and systems are considered in the analysis, as they may increase considerably the global vulnerability and risk of the systems or the system of systems. SYNER-G methodology encompasses in an integrated way all aspects in the chain, from hazard to the physical vulnerability and loss assessment of components and systems and to the socio-economic impacts of earthquakes, accounting for all relevant uncertainties within an efficient quantitative simulation scheme, modeling interactions between the multiple components and systems.

In the frame of this large collaborative project, an extensive literature review of fragility functions for all elements at risk has been made. Based on a new taxonomy and typology that considers the distinctive European features, existing fragility curves and associated uncertainties have been critically reviewed and new or existing fragility curves have been proposed.

The book presents in a comprehensive way the latest developments on the fragility functions encompassing the work done in SYNER-G and in some other parallel projects, as for example in case of masonry buildings. It is organized in several chapters devoted to different systems. For each system, the new taxonomy and classification scheme is presented and then, after a review of the existing fragility functions, the most relevant fragility functions, new ones and selected from the international literature, for the different components are highlighted. Uncertainties are discussed throughout the book and in particular at the beginning, where the framework of the treatment of uncertainties in view of the construction of fragility functions is outlined. Recommendations are also provided for the selection of the most adequate fragility functions. A special tool has been also developed in the frame of SYNER-G to store, visualize and manage a large number of fragility function sets. The tool can store functions for a wide range of elements at risk, and has features that allow these functions to be harmonized in terms of intensity measure type and limit state. The tool is provided, together with a collection of European fragility functions for buildings, as an electronic supplement to this book (extras.springer.com).

The ambition is to offer to the European and international scientific and engineering community a standard reference book of the present state of the art in fragility models for the seismic risk analysis of most elements at risk, and at the same time to highlight the remaining gaps and the necessary future developments on this important topic. The present book is the first of the two volumes that present the main achievements and results of SYNER-G. The second one entitled *Systemic Seismic Vulnerability and Risk Assessment of Complex Urban, Utility, Lifeline Systems and Critical Facilities. Methodology and Applications*, demonstrates the integrated methodological framework of SYNER-G, which is applied in selected case studies, also using fragility curves that are included in the present book.

The Editor would like to acknowledge the contributors to the individual chapters who are listed under each chapter. Most of them actively participated in SYNER-G. In particular special acknowledgement to Sergio Lagomarsino, Serena Cattari, Tiziana Rossetto and Dina D'Ayala, who without being partners in SYNER-G accepted the invitation to contribute to this volume.

Finally, the support of the two co-editors, Helen Crowley and Amir M. Kaynia, and in particular the devotion and hard work of Dr. Sotiris Argyroudis to the preparation of this volume is gratefully acknowledged.

Thessaloniki, Greece K. Pitilakis

List of Acronyms

AC	Asbestos cement
AC	Alternating current
BCL	Bars-connecting line
BDG	Buildings
BN	Bayesian networks
BS	Bar systems
C	Concrete
CI	Cast iron
CIDH	Cast-in-drilled-holes
CCD	Central composite design
CoV	Coefficient of variation
CSM	Capacity spectrum method
DBV	Displacement based vulnerability
DI	Ductile iron
DM	Damage state
DS	Damage state
DVE	Damage value
EC2	Eurocode 2
EC8	Eurocode 8
EDP	Engineering demand parameter
EMS98	European Macroseismic Scale
EPN	Electric power network
EPG	Emergency power generator
EQL	Equivalent linear analysis
FE	Finite element
FFM	Fragility function manager
ffs	Fragility function set
FS	Factor of safety
FOSM	First order second moment method
GEM	Global earthquake model
GMICEs	Ground motion to intensity conversion equations

GMPE	Ground motion prediction equations
GIS	Geographical information systems
GMPGV	Geometric mean of PGV
HDPE	High density polyethylene
IDA	Incremental dynamic analysis
IGMCEs	Intensity to ground motion conversion equations
IM	Intensity measure
IML	Intensity measure level
IMT	Intensity measure type
ISDR	Inter-story drift ratio
IO	Immediate Occupancy
JMA	Japan Meteorological Agency
LHS	Latin hypercube sampling
LN	Lognormal
LS	Limit state
MBSR	Matrix-based system reliability methods
MC	Monte Carlo
MCS	Mercalli-Cancani-Sieberg intensity scale
MDOF	Multi degree of freedom
MDPE	Medium density polyethylene
MMI	Modified Mercalli intensity
MSK81	Medvedev-Sponheuer-Karnik Intensity Scale
MV-LV	Medium voltage – low voltage
MRI	Mean return interval
NDA	Nonlinear dynamic analysis
NSA	Nonlinear static analysis
NLTHA	Non-linear time history analysis
OLE	Operating level earthquake
PBVA	Performance based vulnerability assessment
PI	Performance indicator
PGA	Peak ground acceleration
PGD	Permanent ground deformation
PGV	Peak ground velocity
PGS	Peak ground strain
PE	Polyethylene
PLS	Performance limit states
POSA	Push over static analysis
PSI	Parameterless scale of intensity
PVC	Polyvinyl chloride
RC or R/C	Reinforced concrete
RMS	Root mean square of the acceleration
SCADA	Supervisory control and data acquisition
SDOF	Single degree of freedom
SM	Simplified method

SSWP	Strong spandrels weak piers
TGD	Transient ground deformation
ULS	Ultimate limit state
UPS	Uninterruptible power system
WS	Welded steel
WSSP	Weak spandrels strong piers
WSAWJ	Welded-steel arc-welded joints
WSCJ	Welded-steel caulked joints
WSGWJ	Welded-steel gas-welded joints

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List of Symbols

A_u	Ultimate spectral acceleration
A_y	Spectral acceleration at yielding
ASI	Acceleration spectrum intensity
C_i	Capacity of RC structural elements
C	Number of casualties as percentage of the population
C_{YY}	Covariance matrix
CL	Connectivity loss
Γ_X	Participation factor of the equivalent SDOF system
D_{YY}	Standard deviation matrix
D	Displacement
D_{LS}	Limit state threshold of displacement
D_u	Ultimate spectral displacement
D_y	Spectral displacement at yielding
DI	Damage index
DV	Vector of decision variables
DM	Vector of random damage measures
E	Modulus of elasticity
G	Shear modulus
G_o	Initial shear modulus
HTC	Hospital treatment capacity
HTD	Hospital treatment demand
I	Macroseismic intensity
IM	Intensity measure
IM_{LS}	Median value of the lognormal distribution of the intensity measure im_{LS} that produces the LS threshold
IQR	The inter-quartile range of the normal distribution
K	Corrective factor
K_1	Corrective factor
K_2	Corrective factor
L	Length
M	Bending moment

M_{Rd}	Design value of bending moment capacity
N	Axial force
N	Number of stories
N_{T1+T2}	Number of severely injured people
N_{T3}	Number of lightly injured people
N_{T4}	Number of deaths
N_{cas}	Total number of casualties
N_{pop}	Population
$P(\cdot)$	Probability
Q	Ductility index
R_{YY}	Correlation matrix
RR	Repair rate
R^2	Coefficient of determination
S_1	Medical severity index
S_2	Injuries severity index
S_a	Spectral acceleration
$S_a(T)$	Spectral acceleration at period T
$S_d(T)$	Spectral displacement at period T
SI	Spectrum intensity
T	Period
T_e	Elastic fundamental-mode period
T_{LS}	Inelastic period corresponding to a specific limit state
T_y	Elastic period
$T_{1.0}$	1-second period
V	Vulnerability index
V_{s30}	Shear wave velocity in the upper 30 m of the soil profile
V_s	Shear wave velocity
X	Vector of probabilistically qualified random quantities
c	Apparent wave propagation velocity
c_v	Coefficient of variation
h	Height
f_{cm}	Mean material strength for concrete
f_{ym}	Mean material strength for steel
f_X	Base shear at ground floor for unity gross area
k	Parameter in casualties model
k_y	Yield acceleration coefficient
m	Median of normal distribution
$m_X{}^*$	Equivalent mass of the equivalent SDOF system
q	Behaviour factor
t_m	Mean duration of a surgical operation
v_p	Peak horizontal particle velocity
Δ	Drift
Φ	Standard cumulative probability function
α	Factor accounting for the efficiency of the hospital emergency plan

α_g	Peak ground acceleration
β	Standard deviation of lognormal distribution
β	Factor accounting for the quality, training and preparation of hospital operators
β_{tot}	Total standard deviation or total uncertainty
β_C	Uncertainty in capacity
β_D	Uncertainty in demand
β_{ME}	Dispersion in mechanical parameters
β_{GE}	Dispersion in geometric parameters
β_{ST}	Dispersion in structural detailing
β_{MO}	Dispersion in numerical modeling
β_{RE}	Dispersion in record to record
β_a	Dispersion in attenuation laws
β_{LS}	Dispersion of the LS
β_H	Uncertainty in the derivation of the hazard curve
β_T	Uncertainty in the definition of the Limit State threshold
γ	Shear strain
γ_1	Number of functioning operating theatres
γ_2	System-survival Boolean function
γ_c	Unit weight of concrete
γ_m	Partial safety factor for the resistance
δ	Displacement
$\varepsilon_{q,d}$	Design shear strain due to translational movements
$\varepsilon_{t,d}$	Total nominal design strain
ε_c	Error in element capacity model
ε_{cas}	Error in casualties model
ζ	Factor accounting for the proportion of patients that require surgical attention
$\eta(\xi_{LS})$	Damping correction factor
θ	Rotation
θ_{max}	Maximum interstory drift ratio
λ	Logarithmic mean
μ	Median value
μ_D	Mean damage grade
ξ_0	Initial damping
ξ_H	Maximum hysteretic damping
σ_X	Average vertical compressive stress at the middle height of the first level masonry piers
τ_X	Masonry shear strength at the ground level
φ	Curvature

Contents

Chapter 1
Introduction

Kyriazis Pitilakis, Helen Crowley, and Amir M. Kaynia

Abstract This chapter outlines the main components, parameters and methods to derive fragility functions, which can be used in seismic risk assessment of different engineering systems and components at urban and regional scale. It provides the means of understanding the main factors governing this topic, introducing the subjects that will be extensively described and discussed in the subsequent chapters, where the fragility curves for buildings and all important components of the systems and infrastructures will be described in detail.

1.1 Background

Seismic risk assessment can be defined is the estimation of the probability of expected damages and losses due to seismic hazards. The majority of currently available approaches to assess the potential losses for a wide group of exposed elements rely on the availability of relevant fragility curves. In the past decades, the field of seismic risk assessment has witnessed remarkable developments. A detailed

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