

ATC-13

Earthquake Damage Evaluation

Data for California

by

APPLIED TECHNOLOGY COUNCIL
555 Twin Dolphin Drive, Suite 550
Redwood City, CA 94065

Funded by:

FEDERAL EMERGENCY MANAGEMENT AGENCY
Washington, DC

PRINCIPAL INVESTIGATOR
Christopher Rojahn

CO-PRINCIPAL INVESTIGATOR
Roland L. Sharpe

**CONSULTANT ON EARTHQUAKE
STUDIES**
Roger E. Scholl

**CONSULTANT ON STATISTICS AND
PROBABILITY**
Anne S. Kiremidjian

**CONSULTANT ON INVENTORY
METHODOLOGY**
Richard V. Nutt

PROJECT ENGINEERING PANEL
Milton A. Abel
J. Marx Ayres
John A. Blume
George E. Brogan
Robert Cassano
Ted M. Christensen
Henry J. Degenkoib
Homer H. Given
Henry J. Lagorio
LeVal Lund
Ferd F. Mautz
Roland L. Sharpe
James L. Stratta

PREFACE

In October 1982 the Federal Emergency Management Agency (FEMA) awarded Applied Technology Council (ATC) a contract to develop earthquake damage evaluation data for facilities in California. FEMA is planning to use these data and companion loss estimation and inventory methodology to estimate the economic impacts of a major California earthquake on the state, region, and nation.

Because the required earthquake damage, loss and inventory data were not available in the literature, ATC and FEMA agreed that the best way to develop the required data was to draw on the experience and judgment of seasoned earthquake engineers. Accordingly, ATC established an advisory Project Engineering Panel (PEP) composed of senior-level specialists in earthquake engineering to provide the input necessary to develop consensus damage/loss estimates as well as advise on other aspects of the project. Their work was augmented by 58 additional earthquake specialists who were engaged to participate in the questionnaire processes used to develop the consensus damage/loss estimates. Detailed technical work on the project was conducted by ATC staff, three staff consultants, and three graduate-student/post-doctorate staff.

This report¹ includes pertinent background information, detailed descriptions of the methodology used to develop the required earthquake damage/loss estimates and inventory information, and tables and figures showing the damage/loss estimates developed. Included are damage probability matrices for 78 different facility types as well as estimates of the time required to restore damaged facilities to their pre-earthquake usability.

ATC gratefully acknowledges the numerous individuals who contributed to the development of this report. R. E. Scholl served as the consultant on earthquake losses, wrote a substantial portion of the text, and contributed significantly to the overall development of the concepts and data presented herein. A. S. Kiremidjian, who served as the consultant on statistics and probability, developed the questionnaires used to query the earthquake specialists and was responsible for data analysis and presentation.

R. V. Nutt, who served as the consultant on inventory methodology, developed both the inventory data and methodology. T. Anagnos, A. C. Boissonnade, and R. J. Nielsen (graduate-student/post-doctorate staff from Stanford University, Dept. of Civil Engineering) assisted in data acquisition and analysis. M. Quinonez, N. Day, and C. Day of the ATC staff typed and assisted in the compilation of the final report, and S. Rush of Rdd Consultants served as technical editor.

Special recognition goes to the 13-member PEP, without whose continual advice and support this project would have never been possible, and to Robert R. Wilson, FEMA Project Officer, who provided important guidance and patient, continual support throughout the duration of the project.

Christopher Rojahn (Principal Investigator)
ATC Executive Director

¹FEMA footnote: The research forming the basis for this publication was conducted pursuant to a contract with the Federal Emergency Management Agency. The substance of such research is dedicated to the public. The authors and publisher are solely responsible for the accuracy of statements or interpretations contained herein.

TABLE OF CONTENTS

<u>TITLE</u>	<u>PAGE</u>
PREFACE	i
EXECUTIVE SUMMARY	1
CHAPTER 1. INTRODUCTION	11
1.1 Organization of Report	12
CHAPTER 2. EARTHQUAKE LOSSES AND LOSS MECHANISMS:	
OVERVIEW AND METHODOLOGY	15
2.1 Categories of Earthquake Losses	15
2.1.1 Direct Physical Damage	15
2.1.2 Social Loss	18
2.1.3 Economic Loss	18
2.2 Factors Affecting Earthquake Losses	22
2.2.1 Structure/Facility	22
2.2.2 Ground Shaking Severity/Intensity	26
2.2.3 Collateral Hazards	29
2.2.3.1 Ground Failure	29
2.2.3.2 Fault Rupture	32
2.2.3.3 Inundation	34
2.2.3.4 Fire	36
2.2.4 Occupancy	40
2.2.5 Facility Use	42
2.3 Quantification of Earthquake Losses	42
2.3.1 General Mathematical Form For Loss Estimation	42
2.3.2 Procedure for Estimating Direct Physical Damage	46
2.3.3 Procedure for Estimating Deaths and Injuries	48
2.3.4 Procedure for Estimating Loss of Function and Restoration Time	48
2.4 System Effects on Earthquake Losses	48
CHAPTER 3. FACILITY CLASSIFICATIONS	49
CHAPTER 4. INVENTORY METHODOLOGY	57
4.1 General	57
4.1.1 Scope of the Inventory Problem	57
4.1.2 Data Needed for Complete Inventory	57
4.1.3 Spatially Based Facility Inventory	58
4.1.4 Limitations of the Proposed Inventory Methodology	66
4.2 Available Sources of Inventory Data	66
4.2.1 FEMA Databases	66
4.2.1.1 FEMA Economic Data Files	67
4.2.1.2 The National Shelter Survey	67
4.2.2 Engineering Economics Associates Database	74
4.2.3 Census Data	74
4.2.4 Insurance Maps and Files	74
4.2.4.1 Sanborn Maps	74
4.2.4.2 Insurance Services Office Files	75

TABLE OF CONTENTS (CONT.)

	TITLE	PAGE
4.2.5	County Assessors' Data	75
4.2.6	State and Local Government Agencies	76
4.2.7	Commercial and Industrial Sources	76
4.2.8	Land Use Maps and Aerial Photographs	76
4.2.9	U.S. Geological Survey	76
4.2.10	Economic and Geographic Information Agencies	77
4.2.11	California Division of Mines and Geology	77
4.2.12	Expert Opinion	77
4.3	Other Inventory Methodologies	77
4.3.1	Algermissen, Steinbrugge and Lagorio	77
4.3.2	Gates and Scawthorn (Dames & Moore)	78
4.3.3	Arnold and Eisner	78
4.3.4	Gulliver	78
4.3.5	Algermissen and Steinbrugge	78
4.3.6	Association of Bay Area Governments	78
4.3.7	Southern California Earthquake Preparedness Project	78
4.3.8	Scientific Services	78
4.3.9	Expert Systems Approach	79
4.4	Proposed Inventory Methodologies	79
4.4.1	Level 1—Use of Existing Facility Specific Databases	82
4.4.2	Level 2—Synthesis of Facility Inventories from FEMA and EEA Economic Data	90
4.4.3	Level 3—Synthesis of Facility Inventories from Population or Other Data	93
4.4.4	Estimating the Distribution of Earthquake Engineering Facility Classifications	93
4.4.4.1	Distribution of Building Types	98
4.4.4.2	Distribution of Other Facility Types	118
4.4.5	Development of Building Size - Employee Number Relationships	125
4.4.6	Geologic Hazard Inventories	125
4.4.7	Estimating Building Contents and Equipment	125
4.4.8	Estimating Number of Occupants	125
4.5	Inventory Procedures to be used for Each Social Function Classification	125
4.5.1	Residential Facilities	128
4.5.2	Commercial Facilities	128
4.5.2.1	Retail Trade	128
4.5.2.2	Wholesale Trade	128
4.5.2.3	Personal and Repair Service	129
4.5.2.4	Professional, Technical, and Business Services	129
4.5.2.5	Health Care Services	129
4.5.2.6	Entertainment and Recreation	129
4.5.2.7	Parking	129
4.5.3	Industrial Facilities	129
4.5.4	Agricultural and Mining Facilities	130
4.5.5	Religious and Nonprofit Facilities	130
4.5.6	Government Facilities	130
4.5.7	Educational Facilities	130

TABLE OF CONTENTS (CONT.)

<u>TITLE</u>	<u>PAGE</u>
4.5.8 Transportation Facilities	131
4.5.9 Utilities	132
4.5.10 Communication Facilities	133
4.5.11 Flood Control Facilities	133
4.6 Summary	134
CHAPTER 5. SELECTION OF GROUND MOTION CHARACTERIZATION .	137
5.1 Earthquake Ground Shaking	137
5.2 Seismological Earthquake Shaking Characterizations	138
5.3 Engineering Characterizations of Earthquake Shaking	139
5.4 Ground Shaking Characterization Selection	140
5.5 Use of the MMI Scale	140
CHAPTER 6. LITERATURE SURVEY OF EARTHQUAKE DAMAGE .	143
6.1 Observed Earthquake Effects on Buildings	143
6.1.1 Data for Low-Rise Wood-Frame Buildings	143
6.1.2 Data for Low-Rise Unreinforced Masonry Buildings	147
6.1.3 Data for Low-Rise Reinforced Masonry Buildings	147
6.1.4 Data for High-Rise Steel Buildings	147
6.1.5 Data for High-Rise Concrete Buildings	149
6.1.6 Data for Other Buildings	149
6.2 Observed Earthquake Effects on Bridges	149
6.3 Observed Earthquake Effects on Tunnels	151
6.4 Observed Earthquake Effects on Underground Pipelines	155
6.5 Observed Earthquake Effects on Earth Dams	161
CHAPTER 7. DIRECT DAMAGE FROM GROUND SHAKING FROM EXPERT OPINION .	167
7.1 General Description	167
7.2 Questionnaire Format	175
7.3 Summary of the Questionnaire Process	176
7.4 Statistical Analysis of the Questionnaire Results	186
7.5 Damage Probability Matrices	188
7.6 Limitations of the Delphi Method and Resulting Data	219
7.7 Effect of Design and Construction Quality on Damage Estimation .	219
CHAPTER 8. DIRECT DAMAGE FROM COLLATERAL HAZARDS .	223
8.1 Ground Failure	223
8.1.1 Poor Ground	224
8.1.1.1 Types of Liquefaction Failures	225
8.1.1.2 Factors Affecting Liquefaction	226
8.1.1.3 Identification of Liquefiable Soils	227
8.1.1.4 Ground Failure Potential	229
8.1.1.5 Estimating Damage Caused by Poor Ground/Liquefaction	229
8.1.2 Landslides	231
8.1.2.1 Landslide Classification and Historical Experience	231
8.1.2.2 Landslide Susceptibility	232

TABLE OF CONTENTS (CONT.)

	<u>TITLE</u>	<u>PAGE</u>
8.2	8.1.2.3 Estimating Damage Caused by Landslides	236
Fault Rupture		236
8.2.1	Faulting and Local Deformation	241
8.2.1.1	Location and Type of Fault	242
8.2.1.2	Length of Break	242
8.2.1.3	Displacement	245
8.2.1.4	Width of Disruption	246
8.2.1.5	Local Deformation	246
8.2.2	Effects of Faulting and Local Deformation on Structures	247
8.2.3	Estimating the Effects of Faulting	247
8.3	Inundation	248
8.3.1	Tsunami	248
8.3.2	Seiche	249
8.3.3	Landslide-Induced Water Waves	249
8.3.4	Reservoir Failure	249
8.3.5	Damage from High-Velocity Water	249
8.3.6	Estimating Damage from Earthquake-Caused Inundation	251
8.4	Fire Following Earthquakes	252
8.4.1	Factors Affecting Fire Loss	252
8.4.2	Fires in Recent Earthquakes	252
8.4.3	Quantitative Methods for Predicting Fires	254
8.4.4	Proposed Fire Scenarios for this Project	255
8.4.4.1	Metropolitan San Francisco Bay Area	255
8.4.4.2	Greater Los Angeles Area	256
CHAPTER 9. COLLATERAL LOSSES		257
9.1	Death and Injuries	257
9.2	Loss of Function and Restoration Time	259
9.2.1	Factors Affecting Loss of Function and Restoration Time	259
9.2.2	Available Data on Loss of Function for Individual Facilities	261
9.2.3	Available Data on Loss of Function for Lifelines Systems	262
9.2.4	Procedure for Estimating Loss of Function and Restoration Time	268
9.2.4.1	Assumptions for Estimating Loss of Function and Restoration Time	268
9.2.4.2	Methodology for Evaluating the Impact of Lifeline Failures on Loss of Function	269
9.2.4.3	Loss of Function and Restoration Time from Expert Opinion	275
9.2.4.4	Development of Function Restoration Curves	286
9.2.4.5	Summary of Procedure for Estimating Loss of Function/Restoration Time	286
CHAPTER 10. CONCLUDING REMARKS AND RECOMMENDATIONS		307
REFERENCES		311
APPENDIX A: PROJECT PARTICIPANTS		329

TABLE OF CONTENTS (CONT.)

	<u>TITLE</u>	<u>PAGE</u>
APPENDIX B:	SEISMOLOGICAL INTENSITY SCALES	335
APPENDIX C:	MMI - QUANTITATIVE GROUND MOTION RELATIONS . .	351
APPENDIX D:	MOTION-DAMAGE RELATIONSHIP DATA FOR BUILDINGS FROM THE LITERATURE	349
APPENDIX E:	SAMPLE DAMAGE-FACTOR QUESTIONNAIRE	409
APPENDIX F:	EXPERT RESPONSES FOR MOTION-DAMAGE RELATIONSHIPS	415
APPENDIX G:	STATISTICS OF EXPERT RESPONSES FOR MOTION- DAMAGE RELATIONSHIPS	443
APPENDIX H:	SAMPLE LOSS OF FUNCTION QUESTIONNAIRE	457
APPENDIX I:	EXPERT RESPONSES FOR LOSS OF FUNCTION AND RESTORATION TIME	463
APPENDIX J:	APPLIED TECHNOLOGY COUNCIL PROJECTS AND REPORT INFORMATION	485