

Springer Series in Geomechanics and Geoengineering

Editors: Wei Wu · Ronaldo I. Borja

Ikuo Towhata

Geotechnical Earthquake Engineering

Professor Wei Wu, Institut für Geotechnik, Universität für Bodenkultur, Feistmantelstraße 4, 1180 Vienna, Austria.
E-mail: wei.wu@boku.ac.at

Professor Ronaldo I. Borja, Department of Civil and Environmental Engineering, Stanford University, Stanford, California
94305-4020, USA. E-mail: borja@stanford.edu

Author

Ikuo Towhata
Professor of Geotechnical Engineering
Department of Civil Engineering
University of Tokyo
7-3-1, Hongo, Bunkyo-Ku
Tokyo 113-8656
Japan
Email:towhata@geot.t.u-tokyo.ac.jp

ISBN 978-3-540-35782-7

ISBN 978-3-540-35783-4 (eBook)

DOI 10.1007/978-3-540-35783-4

Springer Series in Geomechanics and Geoengineering

Library of Congress Control Number: 2008920290

© 2008 Springer-Verlag Berlin Heidelberg

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Type setting by the authors and Scientific Publishing Services Pvt. Ltd.

Printed in acid-free paper

5 4 3 2 1 0

springer.com

地盤
耐震
工學



Preface

This book is a product of my long-term activities in both education and research. Its publication was made possible by a financial support supplied by the Ministry of Education, Culture, Sports, Science and Technology. As for education, I was told for the first time in 1985 to teach soil dynamics in Asian Institute of Technology in Bangkok, Thailand. I collected experimental and field findings from many publications and made a small series of handouts. Since computer technologies were not well advanced in mid 80s, the handouts were products of cut-and-paste in the physical sense. Many pages were even handwritten. Afterwards, I started to teach the same subject in 1995 at University of Tokyo. Since then I have added more information from field investigation and laboratory tests as well as analyses. It has become possible to put all in an electronic media that makes teaching easier. Readers can find that this book includes Japanese writing among English text. This is because I use this text for teaching in Tokyo.

The main aim of this book is a collection of data which is useful in understanding the state-of-art technology and its application to new topics. Understanding the fundamental issues is important because practice makes use of many assumptions, hypotheses, and way of thinking. It has been my policy to show reasons why practice employs those ideas by showing experimental and field backgrounds. This idea does not change even today.

Collecting the background information is not very easy for an individual person. It is necessary to read many publications; some were published in the first half of the 20th Century, and others in domestic publications. Not being impossible, this information collection is firstly a time-consuming business. Secondly, the access to old publication may not be easy to everybody. I am therefore attempting in this book to collect information as much as possible so that the new generation of readers can save time in studying. Many figures were therefore reproduced from the original publications. Moreover, I tried to visit important sites and take photographs in order to show the ideas in practice to be meaningful. Although the result is not perfect, information in this book will be helpful when readers have to understand the meaning of present practice and improve it in future. This is particularly important because the development of our society generates new kinds of problems and new approach is continuously required.




One major problem in this book is the enormous amount of information. For very young readers who have just started geotechnical engineering and soil mechanics, it is more important to get the overall scope than learning details. The total number of pages and contents in this book may prevent their efforts. In this regard, I decided to classify the contents into three categories; elementary, advanced, and miscellaneous. Readers can pick up only pages of their interest in place of reading from the first page to the last. The miscellaneous content is not necessarily less important; sometimes many interesting topics are therein found. It is recommendable therefore that young readers take a quick look at those pages as well. On the other hand, it is not expected for readers to start reading from the first page and continue till the last.

I do hope that information in this book will help readers develop their knowledge and career in the discipline of geotechnical engineering. Certainly the contents of this book miss many important issue. I am going to show additions and modifications in my home page. Readers are advised to visit occasionally the site of Geotechnical Engineering Laboratory, Department of Civil Engineering, University of Tokyo (URL : <http://geotle.t.u-tokyo.ac.jp>).

Ikuo Towhata
June, 2007.















List of Contents

The following symbols indicate the types of respective chapters;

Chapters concerning elementary topics : ,
advanced topics : , and
miscellaneous topics : .




PART 1 KNOWLEDGE OF SOIL MECHANICS

Chapter 1 BASIC PRINCIPLES IN SOIL MECHANICS




Section 1.1	PHYSICAL PROPERTIES OF SOIL	4	
Section 1.2	WEIGHT AND DENSITY OF SOIL	6	
Section 1.3	EFFECTIVE STRESS AND PORE WATER PRESSURE	7	
Section 1.4	CONSIDERATION AND VOLUME CHANGE	10	
Section 1.5	SHEAR DEFORMATION AND STRENGTH OF SAND	12	
Section 1.6	DILATANCY OR SHEAR-INDUCED VOLUME CHANGE	13	
Section 1.7	UNDRAINED OR CONSTANT-VOLUME SHEAR TEST	15	
Section 1.8	EXCESS PORE WATER PRESSURE AND STRESS PATH DIAGRAM	16	
Section 1.9	TRIAXIAL SHEAR DEVICE	17	
Section 1.10	MEMBRANE PENETRATION	19	
Section 1.11	ELEMENTARY DYNAMICS	21	
Section 1.12	STANDARD PENETRATION TEST	22	
Section 1.13	FLOW OF GROUND WATER	24	
Section 1.14	SHEAR BAND	26	

PART 2 PROBLEMS CONCERNING SHAKING OF SOFT GROUND UNDERGOING EARTHQUAKE LOADING













Chapter 2 INTRODUCTION

Section 2.1	OBJECTIVES OF EARTHQUAKE GEOTECHNICAL ENGINEERING	32	
Section 2.2	GEOTECHNICAL PROBLEMS ENCOUNTERED DURING EARTHQUAKES	33	
Section 2.3	SCHEMATIC DIAGRAM TO SHOW RELATIONSHIP AMONG GEOTECHNICAL SEISMIC PROBLEMS	34	
















Chapter 3 SEISMOLOGICAL KNOWLEDGE

Section 3.1	RUPTURE OF FAULT AS A CAUSE OF EARTHQUAKE	36	
Section 3.2	REGIONS WHERE BIG EARTHQUAKE IS LIKELY TO OCCUR	38	
Section 3.3	RESERVOIR-TRIGGERED SEISMICITY	40	









Chapter 4 WAVE PROPAGATION IN ELASTIC MEDIUM































Section 4.1	EARTHQUAKE WAVES : S WAVE	43	
Section 4.2	EARTHQUAKE WAVES : P WAVE	44	
Section 4.3	IDEALIZATION OF VERTICAL WAVE PROPAGATION	46	
Section 4.4	VERTICAL PROPAGATION OF “S” WAVE IN LEVEL GROUND	47	
Section 4.5	SOLUTION OF S-WAVE PROPAGATION IN REAL NUMBERS	48	
Section 4.6	EXERCISE NO.1 ON AMPLIFICATIN OF GROUND MOTION	50	
Section 4.7	EARTHQUAKE WAVES: RAYLEIGH WAVE	51	
Section 4.8	EARTHQUAKE WAVES: LOVE WAVE	53	
Section 4.9	RESPONSE OF ELASTIC GROUND TO SURFACE EXCITATION	54	
Section 4.10	WAVE TRANSMISSION AND REFLECTION AT INTERFACE	55	
Section 4.11	CALCULATION OF SEISMIC WAVE ENERGY	56	
Section 4.12	TRAFFIC-INDUCED GROUND VIBRATION	57	

Chapter 5 EARTHQUAKE EFFECTS











Section 5.1	INTENSITY OF EARTHQUAKE MOTION	60	
Section 5.2	REVISED EARTHQUAKE INTENSITY	62	
Section 5.3	INSTRUMENTAL DETERMINATION OF SEISMIC INTENSITY	63	
Section 5.4	EARTHQUAKE MAGNITUDES	65	
Section 5.5	TIME HISTORY OF GROUND MOTION	67	
Section 5.6	EFFECTS OF LOCAL SOIL CONDITIONS ON MAXIMUM ACCELERATION	68	
Section 5.7	SOME FAMOUS EARTHQUAKE MOTION RECORDS	69	
Section 5.8	GROUND MOTION DURING 1985 MEXICAN EARTHQUAKE	70	
Section 5.9	POWER OF ACCELERATION TIME HISTORY	72	
Section 5.10	DISTANCE FROM SOURCE OF EARTHQUAKE	73	
Section 5.11	ESTIMATION OF INTENSITY OF EARTHQUAKE MOTION	74	
Section 5.12	ESTIMATION OF DURATION OF EARTHQUAKE MOTION	75	
Section 5.13	DETERMINATION OF DESIGN EARTHQUAKE MOTION	76	
Section 5.14	SEISMIC DAMAGE IN TRADITIONAL HOUSES	78	
Section 5.15	RECONNAISSANCE STUDY OF EARTHQUAKE-INDUCED DAMAGE	83	

Chapter 6 DYNAMIC RESPONSE ANALYSIS

























Section 6.1	RATE-DEPENDENT BEHAVIOUR OF CLAY	88	
Section 6.2	SIGNIFICANCE OF COMPLEX ANALYSIS	89	
Section 6.3	TRANSIENT RESPONSE	92	
Section 6.4	ANALYSES IN FREQUENCY DOMAIN AND TIME DOMAIN	93	
Section 6.5	NUMERICAL INTEGRATION OF EQUATION OF MOTION IN THE TIME DOMAIN	95	
Section 6.6	NEWMARK’S β METHOD	97	
Section 6.7	INTRODUCTION TO SEISMIC RESPONSE ANALYSIS	100	
Section 6.8	AMPLIFICATION OF MOTION IN SURFACE ALLUVIUM	102	

Section 6.9	SIGNIFICANCE OF OUTCROP MOTION	104	
Section 6.10	SEISMIC RESPONSE OF MULTI-LAYERED GROUND	106	
Section 6.11	AMPLIFICATION OF MOTION AT THE TOP OF HILL	107	
Section 6.12	ANALYSIS ON HILL-INDUCED AMPLIFICATION	108	
Section 6.13	CALCULATED AMPLIFICATION EFFECTS OF HILLY TOPOGRAPHY	110	
Section 6.14	OBSERVED TOPOGRAPHIC EFFECTS	111	
Section 6.15	THEORY OF BESSEL FUNCTIONS	113	
Section 6.16	INFINITE BOUNDARY CONDITION	114	
Section 6.17	EXERCISE NO.2 OF DYNAMIC RESPONSE ANALYSIS ON ELASTIC GROUND	118	
Chapter 7 PSEUDOSTATIC LIMIT EQUILIBRIUM ANALYSIS			
Section 7.1	SEISMIC COEFFICIENT	121	
Section 7.2	MODIFIED METHOD OF SEISMIC COEFFICIENT	124	
Section 7.3	VERTICAL MOTION	126	
Section 7.4	DIRECTION OF SEISMIC INERTIA FORCE IN DESIGN	127	
Chapter 8 FIELD INVESTIGATION			
Section 8.1	FIELD INVESTIGATION ON SHEAR WAVE VELOCITY	130	
Section 8.2	SUSPENSION-TYPE DOWNHOLE SURVEY	131	
Section 8.3	CROSS-HOLE SURVEY	133	
Section 8.4	CORRELATION BETWEEN SPT- <i>N</i> AND V_s OF ALLUVIAL SOILS	134	
Section 8.5	CORRELATION BETWEEN SPT- <i>N</i> AND V_s OF GRAVELLY SOILS	136	
Section 8.6	CORRELATION BETWEEN SPT- <i>N</i> AND V_s OF PLEISTOCENE SOILS	137	
Section 8.7	SEISMIC REFRACTION METHOD FOR SUBSURFACE EXPLORATION	138	
Section 8.8	STACKING TECHNIQUE TO REMOVE NOISE FROM SIGNAL	140	
Section 8.9	SWEDISH WEIGHT SOUNDING	142	
Section 8.10	MICROTREMOR	143	
Section 8.11	SUBSURFACE EXPLORATION BY SURFACE WAVE RECORDS	147	
Chapter 9 DYNAMIC RESPONSE OF COMPLEX-MODULUS MODEL			
Section 9.1	COMPLEX STRESS-STRAIN MODELING	150	
Section 9.2	DAMPING RATIO IN SOIL DYNAMICS AND CRITICAL DAMPING RATIO	152	
Section 9.3	DAMPED OSCILLATION OF COMPLEX-MODULUS MODEL	153	
Section 9.4	FORCED OSCILLATION OF COMPLEX-MODULUS MODEL	155	
EXERCISE	CALCULATION OF AMPLIFICATION FACTOR	156	
Section 9.5	WAVE PROPAGATION IN COMPLEX-MODULUS MEDIUM	157	
Section 9.6	SOLUTION OF REAL NUMBERS IN COMPLEX-MODULUS GROUND	159	







XII List of Contents

Section 9.7	OUTCROP AMPLIFICATION IN COMPLEX-MODULUS GROUND	160	
Section 9.8	EXERCISE NO.4 RESPONSE ANALYSIS OF MULTILAYERED DEPOSITS	162	
Section 9.9	VARIATION OF SHEAR MODULUS AT INTERFACE OF SOIL LAYERS	163	
Section 9.10	EQUIVALENT LINEAR MODELING	165	
Section 9.11	THEORY OF FOURIER SERIES	166	
Section 9.12	SPECTRUM ANALYSIS BY FOURIER SERIES	168	
Section 9.13	DYNAMIC ANALYSIS WITH EQUIVALENT LINEAR MODEL	171	
Section 9.14	EXAMPLE OF EQUIVALENT LINEAR ANALYSIS	172	
	EXERCISE NO.5 EQUIVALENT LINEAR METHOD OF ANALYSIS	173	
Section 9.15	DECONVOLUTION OF EARTHQUAKE MOTION	175	
Section 9.16	FURTHER REMARKS ON EQUIVALENT LINEAR MODEL	178	









Chapter 10 LABORATORY TESTS ON DYNAMIC PROPERTIES OF SOILS

Section 10.1	RESONANT COLUMN TEST OF SOILS	181	
Section 10.2	GENERAL PRINCIPLE IN INTERPRETATION OF STRAIN AMPLITUDE EFFECTS ON SHEAR MODULUS AND DAMPING RATIO	183	
Section 10.3	FACTORS THAT AFFECT MODULUS AND DAMPING OF SAND	184	
Section 10.4	FACTORS THAT AFFECT MODULUS AND DAMPING OF CLAY	185	
Section 10.5	SHEAR MODULUS OF SAND AT SMALL STRAIN AMPLITUDE	186	
Section 10.6	EFFECTS OF STRAIN AMPLITUDE ON SHEAR MODULUS	189	
Section 10.7	EFFECTS OF EFFECTIVE STRESS ON SHEAR MODULUS OF SAND	190	
Section 10.8	DAMPING RATIO OF SAND	191	
Section 10.9	RATE DEPENDENT NATURE OF CLAY	192	
Section 10.10	EFFECTS OF PLASTICITY ON CYCLIC BEHAVIOR OF CLAY	193	
Section 10.11	EFFECTS OF DENSITY ON SHEAR MODULUS OF CLAY	194	
Section 10.12	EFFECTS OF AGE ON SHEAR MODULUS OF CLAY	195	
Section 10.13	EFFECTS OF STRAIN AMPLITUDE ON SHEAR MODULUS OF CLAY	196	
Section 10.14	DEGRADATION OF SHEAR MODULUS OF CLAY	197	
Section 10.15	DAMPING RATIO OF CLAY	198	
Section 10.16	EFFECTS OF CONSOLIDATION TIME ON DAMPLING OF CLAY	199	
Section 10.17	G- γ AND h- γ CURVES OF UNDISTURBED SAMPLES	200	
Section 10.18	DYNAMIC DEFORMATION OF GRAVELLY SOILS	201	
Section 10.19	COLLECTING UNDISTURBED SOIL SAMPLES	202	
Section 10.20	FREEZING TECHNIQUE OF SAND SAMPLING	204	
Section 10.21	EXTENT OF SAMPLE DISTURBANCE	205	
Section 10.22	CORRELATION BETWEEN SURFACE VELOCITY AND STRAIN IN SUBSOIL	206	
Section 10.23	NONLINEAR CYCLIC BEHAVIOR OF SODIUM BENTONITE	208	
Section 10.24	NONLINEAR CYCLIC BEHAVIOR OF MUNICIPAL SOLID WASTE	210	









Chapter 11 STRESS-STRAIN MODELS

Section 11.1	HYPERBOLIC AND RAMBERG-OSGOOD STRESS-STRAIN MODELS	218	
Section 11.2	DILATANCY OF SAND SUBJECTED TO CYCLIC DRAINED SHEAR	221	
Section 11.3	THEORY OF ELASTOPLASTICITY	224	
Section 11.4	DILATANCY UNDER CYCLIC LOADING	228	
Section 11.5	MULTI-NONLINEAR SPRING MODEL	230	
Section 11.6	DISCRETE ELEMENT ANALYSIS	232	



Chapter 12 APPLICATION OF SEISMIC INERTIA FORCE

Section 12.1	CALCULATION OF EARTHQUAKE-INDUCED DISPLACEMENT	236	
Section 12.2	CORRELATION BETWEEN RESIDUAL DISPLACEMENT, BASE ACCELERATION AND BASE VELOCITY	238	
Section 12.3	RELATIONSHIP BETWEEN SEISMIC COEFFICIENT AND MAXIMUM ACCELERATION DURING EARTHQUAKES	239	
Section 12.4	BRIEF ANALYSIS ON SEISMIC COEFFICIENT EQUIVALENT TO MAXIMUM ACCELERATION	240	
Section 12.5	SEISMIC EARTH PRESSURE ON RETAINING WALL	241	
Section 12.6	SHAKING MODEL TEST ON SEISMIC EARTH PRESSURE	244	
Section 12.7	COMPARISON OF STATIC AND SEISMIC ACTIVE EARTH PRESSURES	247	
Section 12.8	MODIFIED MONONOBE-OKABE THEORY	248	




























Chapter 13 SEISMIC FORCES EXERTED ON STRUCTURES

Section 13.1	ANALYSIS ON SOIL-STRUCTURE INTERACTION	252	
Section 13.2	SEISMIC DESIGN OF EMBEDDED PIPELINE	255	
Section 13.3	AMPLIFICATION: SOIL COLUMN Vs SPRING-MASS MODEL	257	
Section 13.4	RIGOROUS COMPARISON OF SOIL COLUMN AND EQUIVALENT SPRING-MASS MODEL	259	
Section 13.5	SEISMIC WATER PRESSURE ON WALL	261	
Section 13.6	DYNAMIC EARTH PRESSURE EXERTED BY WATER SATURATED BACKFILL	263	
Section 13.7	DAMAGE IN TUNNELS CAUSED BY EARTHQUAKES	265	
Section 13.8	NODULAR PILE	267	
















Chapter 14 SEISMIC BEHAVIOR OF SLOPES AND EMBANKMENTS

Section 14.1	CLASSIFICATION OF SEISMIC FAILURE OF ARTIFICIAL EMBANKMENT	271	
Section 14.2	EXAMPLE OF SLIDING FAILURE OF EMBANKMENT DUE TO EARTHQUAKES	273	



















XIV List of Contents

Section 14.3	EXAMPLE OF SLUMPING OF EMBANKMENT DUE TO EARTHQUAKES	274	
Section 14.4	STATISTICS ON TYPES OF SUBSIDENCE OF EMBANKMENT DUE TO EARTHQUAKES	276	
Section 14.5	PERFORMANCE-BASED SEISMIC DESIGN	277	
Section 14.6	INQUIRY ON ALLOWABLE SEISMIC DISPLACEMENT	280	
Section 14.7	PRINCIPLE OF PERFORMANCE-BASED SEISMIC DESIGN AND LIFE CYCLE COST	282	
Section 14.8	RESTORATION OF DAMAGED FILL RESTING ON SOFT SOIL	288	
Chapter 15 LANDSLIDES			
Section 15.1	EARTHQUAKE-INDUCED LANDSLIDES	291	
Section 15.2	YUNGAY CITY DESTROYED BY EARTHQUAKE-INDUCED DEBRIS FLOW	294	
Section 15.3	TSAOLING LANDSLIDE IN TAIWAN	296	
Section 15.4	SHEAR TESTS ON LANDSLIDE MECHANISM	298	
Section 15.5	OTHER LANDSLIDES CAUSED BY CHICHI EARTHQUAKE, TAIWAN	301	
Section 15.6	ASSESSMENT OF SEISMIC LANDSLIDE HAZARD	302	
Section 15.7	EARTHQUAKE-INDUCED SUBMARINE LANDSLIDES	306	
Section 15.8	NONSEISMIC SUBMARINE LANDSLIDES	308	
Section 15.9	DERIVATION OF FORMULA FOR APPARENT FRICTIONAL ANGLE	310	
Chapter 16 SEISMIC FAULTS			
Section 16.1	TOPICS RELATED TO FAULT	315	
Section 16.2	EXAMPLE OF REVERSE FAULT	317	
Section 16.3	EXAMPLE OF NORMAL FAULT	319	
Section 16.4	EXAMPLE OF STRIKE-SLIP FAULT	320	
Section 16.5	EFFECTS OF FAULT MOVEMENT ON RUPTURE IN SURFACE SOIL	322	
Section 16.6	DISTORTION AT GROUND SURFACE PRODUCED BY SUBSURFACE FAULT	324	
Section 16.7	EFFECTS OF EARTHQUAKE FAULT ON TUNNELS	326	
Section 16.8	EFFECTS OF EARTHQUAKE FAULT ON EMBEDDED PIPELINES	328	
Section 16.9	FAULT-INDUCED SUBSIDENCE OF GROUND	330	
Section 16.10	TECTONICALLY INDUCED GROUND SUBSIDENCE INTO SEA DURING STRONG EARTHQUAKES IN KOHCHI, JAPAN	331	
Section 16.11	EARTHQUAKE-INDUCED SUBSIDENCE IN OTHER PARTS OF THE WORLD	333	
Section 16.12	GEOTECHNICAL ASPECTS OF TSUNAMI	335	













PART 3 LIQUEFACTION**Chapter 17 FEATURES OF LIQUEFACTION-INDUCED DAMAGES**

Section 17.1	INTRODUCTION TO SEISMIC LIQUEFACTION	344	
Section 17.2	HISTORY OF PROBLEMS AND RESEARCH TOPICS CONCERNING LIQUEFACTION	346	
Section 17.3	LOSS OF BEARING CAPACITY CAUSED BY LIQUEFACTION	347	
Section 17.4	SUBSIDENCE OF EMBANKMENT DUE TO LIQUEFACTION	349	
Section 17.5	FLOATING OF EMBEDDED STRUCTURES	351	
Section 17.6	LATERAL DISPLACEMENT OF RETAINING WALL	352	
Section 17.7	LATERAL MOVEMENT OF LIQUEFIED SLOPE	353	
Section 17.8	GROUND SUBSIDENCE AFTER LIQUEFACTION	356	
Section 17.9	LIQUEFACTION-INDUCED SUBSIDENCE OF RIVER DIKES	357	
Section 17.10	LESSONS FROM 2000 TOTTORIKEN-SEIBU EARTHQUAKE	358	
Section 17.11	EARTHQUAKE INDUCED GROUND SUBSIDENCE	359	
Section 17.12	EARTHQUAKE MOTION RECORDED ON LIQUEFIED GROUND	360	
Section 17.13	SUBSIDENCE OF SHALLOW FOUNDATION DUE TO SUBSOIL LIQUEFACTION	361	
Section 17.14	LIQUEFACTION DAMAGE TO PRIVATE HOUSES	363	
Section 17.15	SUMMARY OF CASE HISTORIES	366	












Chapter 18 MECHANISM OF ONSET OF LIQUEFACTION

Section 18.1	MECHANISM OF LIQUEFACTION	370	
Section 18.2	SAND BOILING	372	
Section 18.3	DISSIPATION OF EXCESS PORE WATER PRESSURE	374	
Section 18.4	PALEOLIQUEFACTION	375	
Section 18.5	EXCAVATION OF BURIED SAND BOIL	376	
Section 18.6	HOT LIQUEFACTION; TRUE OR NOT TRUE	377	
Section 18.7	UNDRAINED SHEAR TESTS OF SAND	378	
Section 18.8	TORSION SHEAR DEVICE WITH HOLLOW CYLINDRICAL SPECIMEN	380	
Section 18.9	EFFECTS OF SUBSURFACE LIQUEFACTION ON INTENSITY OF ACCELERATION RESPONSE AT SURFACE	382	
Section 18.10	CONSOLIDATION AFTER LIQUEFACTION	383	
Section 18.11	LIQUEFACTION POTENTIAL AND SURFACE GEOLOGY	384	
Section 18.12	MAXIMUM DISTANCE OF LIQUEFACTION SITES FROM SOURCE AREA	386	
Section 18.13	EFFECTS OF AGEING ON LIQUEFACTION STRENGTH OF FILL	387	
Section 18.14	LIQUEFACTION IN NATURAL DEPOSIT OF LOOSE SAND	390	
Section 18.15	SIGNIFICANCE OF CYCLIC TRIAXIAL TESTS IN LIQUEFACTION PROBLEMS	391	
Section 18.16	SKEMPTON'S B VALUE	392	
Section 18.17	DEGREE OF SATURATION AND SKEMPTON'S B VALUE	394	
Section 18.18	EFFECTS OF SAMPLE PREPARATION METHODS ON RESISTANCE TO LIQUEFACTION IN LABORATORY SHEAR TESTS	396	

Chapter 19 ASSESSMENT OF LIQUEFACTION POTENTIAL























Section 19.1	SIGNIFICANCE OF STRESS RATIO	402	
Section 19.2	STRESS RATIO IN THE FIELD	404	
Section 19.3	LIQUEFACTION CURVE	406	
Section 19.4	FIELD AND LABORATORY STRESS RATIO	408	
Section 19.5	EFFECTS OF STATIC SHEAR STRESS ON RESISTANCE AGAINST LIQUEFACTION	410	
Section 19.6	IMPORTANCE OF TWO-WAY LOADING IN CYCLIC SHEAR WITH INITIAL STATIC STRESS	412	
Section 19.7	EFFECTS OF K_0 CONSOLIDATION ON LIQUEFACTION RESISTANCE OF SAND	414	
Section 19.8	LIQUEFACTION RESISTANCE OF SAND UNDER K_0 CONDITION AND OVER CONSOLIDATION	415	
Section 19.9	EFFECTS OF CONFINING PRESSURE ON LIQUEFACTION RESISTANCE	418	
Section 19.10	EFFECTS OF IRREGULAR LOADING ON RESISTANCE AGAINST LIQUEFACTION	420	
Section 19.11	CORRECTION OF STRESS RATIO WITH DEPTH	422	
Section 19.12	EFFECTS OF MULTI-DIRECTIONAL SHEAR ON LIQUEFACTION RESISTANCE	424	
































Chapter 20 BEHAVIOR OF SOIL UNDERGOING CYCLIC UNDRAINED LOADING





























Section 20.1	LIQUEFACTION RESISTANCE OF DENSE SAND	430	
Section 20.2	CYCLIC UNDRAINED SHEAR OF GRAVEL	432	
Section 20.3	CYCLIC UNDRAINED SHEAR OF CLAY	433	
Section 20.4	DOES CLAY LIQUEFY?	435	
Section 20.5	LIQUEFACTION OF TAILING MATERIAL	437	
Section 20.6	EMPIRICAL RELATIONSHIP BETWEEN EXCESS PORE WATER PRESSURE AND NUMBER OF LOADING CYCLES	439	
Section 20.7	SIMPLE ASSESSMENTS OF PORE PRESSURE RISE	440	
Section 20.8	USE OF STRAIN ENERGY IN MODELLING OF SOIL UNDERGOING CYCLIC LOADING	441	
Section 20.9	CORRELATION BETWEEN SHEAR STRAIN ENERGY AND EXCESS PORE WATER PRESSURE	442	
Section 20.10	ENERGY CORRELATION OF PORE PRESSURE AT STATES OF SHEAR STRESS	444	
Section 20.11	STRESS-STRAIN BEHAVIOR REPRODUCED FROM ACCELERATION RECORDS	446	

Chapter 21 IN-SITU TESTS ON LIQUEFACTION POTENTIAL OF SUBSOILS

Section 21.1	USE OF SPT FOR ASSESSING LIQUEFACTION POTENTIAL	450	
Section 21.2	SPT- N OBSERVED IN NIIGATA CITY	452	

Section 21.3	ASSESSMENT OF LIQUEFACTION POTENTIAL	453	
Section 21.4	ASSESSMENT OF LIQUEFACTION POTENTIAL BY SPT- <i>N</i> BEFORE 1995	454	
Section 21.5	Exercise No.6: CALCULATION OF FACTOR OF SAFETY AGAINST LIQUEFACTION	456	
Section 21.6	ISSUES FOR FUTURE DEVELOPMENT OF CODE	457	
Section 21.7	REVISED DESIGN PREDICTION OF LIQUEFACTION AFTER 1995 (Part 1; Design load)	458	
Section 21.8	REVISED DESIGN PREDICTION OF LIQUEFACTION AFTER 1995 (Part 2; Resistance against liquefaction)	459	
Section 21.9	FACTOR OF SAFETY AGAINST LIQUEFACTION AND ITS CORRELATION WITH EXTENT OF DAMAGE	461	
Section 21.10	EFFECTS OF FREQUENCY ON LIQUEFACTION RESISTANCE	463	
Section 21.11	USE OF CONE PENETRATION TESTS FOR EARTHQUAKE GEOTECHNICAL SURVEY	464	
Section 21.12	USE OF S-WAVE VELOCITY FOR LIQUEFACTION INVESTIGATION	467	
Chapter 22 POST-LIQUEFACTION BEHAVIOR OF SANDY GROUND			
Section 22.1	GROUND SUBSIDENCE AFTER LIQUEFACTION	471	
Section 22.2	REPEATED LIQUEFACTION	473	
Section 22.3	EFFECTIVE STRESS ANALYSIS WITH HYPERBOLIC MODEL	475	
Section 22.4	EXAMPLE OF EFFECTIVE STRESS ANALYSIS	477	
Section 22.5	ASSESSMENT OF LIQUEFACTION RESISTANCE BY MEASURING SHEAR WAVE VELOCITY	481	
Chapter 23 IMMEDIATE DETECTION OF LIQUEFACTION DAMAGE AND EMERGENCY ACTION			
Section 23.1	RESPONSE SPECTRUM	484	
Section 23.2	SPECTRUM INTENSITY	485	
Section 23.3	IMMEDIATE DETECTION OF SUBSOIL LIQUEFACTION BY USING SPECTRUM INTENSITY (SI) - PRINCIPLE -	489	
Section 23.4	IMMEDIATE DETECTION OF SUBSOIL LIQUEFACTION BY USING SPECTRUM INTENSITY (SI) - EXAMPLE -	491	
Chapter 24 PERMANENT DISPLACEMENT / DEFORMATION OF LIQUEFIED SUBSOIL			
Section 24.1	LATERAL DISPLACEMENT OF LIQUEFIED SUBSOIL	494	
Section 24.2	LATERAL DISPLACEMENT OF QUAY WALL INDUCED BY SUBSURFACE LIQUEFACTION	496	
Section 24.3	STEADY STATE AND STATIC LIQUEFACTION	498	

Section 24.4	SMALL SHAKING TABLE TESTS ON LATERAL DISPLACEMENT	501	
Section 24.5	ROLE PLAYED BY GRAVITY	502	
Section 24.6	BEHAVIOR OF SURFACE DRY CRUST	503	
Section 24.7	SHAKING TABLE TESTS ON LATERAL SOIL DISPLACEMENT	505	
Section 24.8	NEED FOR TESTS ON EXTREMELY LOOSE SANDY DEPOSITS	506	
Section 24.9	SHAKING TABLE TESTS ON EXTREMELY LOOSE DEPOSIT	508	
Section 24.10	SHAKING TABLE TESTS ON DISTORTION OF CAISSON QUAY WALL DURING EARTHQUAKES	509	
Section 24.11	GEOTECHNICAL CENTRIFUGE MODEL TESTS	511	
Section 24.12	LAW OF SIMILITUDE IN DYNAMIC CENTRIFUGE TESTS	513	
Section 24.13	1-G SHAKING TABLE TESTS	517	
Section 24.14	LAW OF SIMILITUDE FOR 1-G SHAKING TESTS	520	
Section 24.15	ONLINE TESTS	524	
Section 24.16	INTERACTION BETWEEN PILE AND LATERAL FLOW OF LIQUEFIED SAND	525	
Section 24.17	EARTH PRESSURE ON WALL EXERTED BY LIQUEFIED SUBSOIL	532	
Chapter 25 PREDICTION OF PERMANENT DISPLACEMENT DUE TO LIQUEFACTION			
Section 25.1	MODE OF DISPLACEMENT	538	
Section 25.2	PRINCIPLE OF MINIMUM POTENTIAL ENERGY	540	
Section 25.3	PRINCIPLE OF LAGRANGEAN EQUATION OF MOTION	542	
Section 25.4	ENERGY THEORY ON FLOW OF LIQUEFIED SUBSOIL	544	
Section 25.5	VARIATIONAL PRINCIPLE AND ITS EULER'S DIFFERENTIAL EQUATION	546	
Section 25.6	PREDICTION OF LATERAL DISPLACEMENT	548	
Section 25.7	CLOSED FORM SOLUTION OF MAXIMUM POSSIBLE DISPLACEMENT	550	
Section 25.8	BOUNDARY CONDITIONS OF SOIL MASS UNDERGOING LATERAL FLOW	551	
Section 25.9	EXAMPLE PREDICTION OF LATERAL DISPLACEMENT	553	
Section 25.10	PARAMETRIC STUDIES ON LATERAL DISPLACEMENT	555	
Section 25.11	THREE DIMENSIONAL PREDICTION OF LATERAL DISPLACEMENT OF LIQUEFIED DEPOSIT	557	
Section 25.12	GLACIER AS SEEN FROM AIRCRAFT	559	
Section 25.13	DRAG FORCE OF EMBEDDED PIPE IN LIQUEFIED MODEL GROUND	560	
Section 25.14	RATE-DEPENDENCY OF LIQUEFIED SAND	561	
Section 25.15	EFFECTS OF CONTINUED SHAKING ON BEHAVIOR OF LIQUEFIED SAND	563	
Section 25.16	ATTEMPT TO MEASURE VISCOSITY OF LIQUEFIED SAND IN SHEAR TESTS	565	
Section 25.17	VISCOSITY OF LIQUEFIED SAND MEASURED IN LABORATORY TESTS	566	

Section 25.18	OBSERVED RATE OF STRAIN DURING LIQUEFACTION-INDUCED GROUND DEFORMATION	570	
Section 25.19	THREE-DIMENSIONAL DYNAMIC ANALYSIS ON LIQUEFACTION-INDUCED PERMANENT DEFORMATION OF GROUND	572	
Section 25.20	EXAMPLE OF THREE-DIMENSIONAL ANALYSIS ON LIQUEFACTION-INDUCED PERMANENT DEFORMATION OF GROUND	574	
Section 25.21	LATERAL LOAD ON PILE FOUNDATION EXERTED BY LATERAL DISPLACEMENT OF LIQUEFIED GROUND	576	
Section 25.22	PASSIVE EARTH PRESSURE EXERTED BY SURFACE UNLIQUEFIED SOIL ON FOUNDATION OF STRUCTURES	577	
Section 25.23	DEFORMATION ANALYSIS BASED ON STRAIN POTENTIAL	578	
Section 25.24	ANALYSIS ON SEISMIC DEFORMATION OF LIYUTAN DAM IN TAIWAN	580	
Section 25.25	ASSESSMENT OF SUBSIDENCE OF RIVER DIKES DUE TO SUBSURFACE LIQUEFACTION BY USING LIMIT EQUILIBRIUM ANALYSIS	582	
Section 25.26	WATER FILM	583	
 Chapter 26 MITIGATION OF LIQUEFACTION-INDUCED DAMAGE			
Section 26.1	PRINCIPLES IN MITIGATION OF LIQUEFACTION-INDUCED DAMAGE	589	
Section 26.2	PRINCIPLES IN PREVENTION OF LIQUEFACTION	592	
Section 26.3	MITIGATION OF LIQUEFACTION-INDUCED GROUND DISPLACEMENT	593	
Section 26.4	SAND COMPACTION PILE FOR DENSIFICATION OF LOOSE SAND	604	
Section 26.5	GROUND IMPROVEMENT BY COMPACTION	606	
Section 26.6	STATIC INSTALLATION OF SAND COMPACTION PILES	609	
Section 26.7	DYNAMIC CONSOLIDATION	610	
Section 26.8	VERIFICATION OF EFFECTS OF DYNAMIC CONSOLIDATION	612	
Section 26.9	RANGE OF SAND DENSIFICATION	613	
Section 26.10	COMPACTION GROUTING	614	
Section 26.11	DISSIPATION OF EXCESS PORE WATER PRESSURE	616	
Section 26.12	LOWERING OF GROUND WATER TABLE	621	
Section 26.13	GROUTING AND DEEP MIXING	622	
Section 26.14	SOLIDIFICATION BY COLLOIDAL SILICA GROUT	625	
Section 26.15	PREMIXING METHOD	631	
Section 26.16	SOIL DENSIFICATION BY BLASTING	633	
Section 26.17	BACKFILLING BY SHREDDED TIRE CHIPS	637	
 Chapter 27 SEISMIC MICROZONATION			
Section 27.1	MICROZONATION FOR INTENSITY OF EARTHQUAKE MOTION	644	
Section 27.2	MICROZONATION FOR LIQUEFACTION	647	

APPENDIX

APPENDIX 1	DERIVATION OF COULOMB'S ACTIVE EARTH PRESSURE FORMULA	652
APPENDIX 2	CONVENIENT EXPRESSIONS IN INTERNATIONAL CONVERSATIONS	662
APPENDIX 3	APPLICATION OF VARIATIONAL PRINCIPLE OF MATHEMATICS TO DEFORMATION ANALYSIS	664
	ANSWER TO EXERCISES	667
	ACKNOWLEDGMENT	677
	INDEX	679

IMPORTANT MESSAGES

Since the total number of pages in this book is large, readers should pick up pages of their interest and not to read unnecessary pages.

Future correction and addition of the contents of this book will be announced in his website in the geotechnical engineering laboratory, Department of Civil Engineering, University of Tokyo. Try <http://geotle.t.u-tokyo.ac.jp>.