



# Geological Engineering

Luis I. González de Vallejo  
Mercedes Ferrer

 CRC Press  
Taylor & Francis Group

A BALKEMA BOOK

# CONTENTS

<b>ABOUT THE AUTHORS</b>	<b>xv</b>	Plasticity	24
<b>CONTRIBUTORS</b>	<b>xvii</b>	Phase relationships	26
<b>FOREWORD</b>	<b>xix</b>	2.3 FLOW OF WATER THROUGH SOILS	28
<b>PREFACE</b>	<b>xxi</b>	Total head. Bernoulli's Theorem	29
		Hydrostatic conditions	29
		Ground water flow	30
		Basic concepts. Head loss and permeability	30
		Hydraulic head and hydraulic gradient	31
		Darcy's law	31
		Steady flow in an isotropic medium	33
		Anisotropic soil conditions	36
		Permeability and water flow in stratified soils	38
<b>PART I – FUNDAMENTALS</b>		2.4 EFFECTIVE STRESS	40
<b>1 INTRODUCTION TO GEOLOGICAL ENGINEERING</b>	<b>3</b>	Soil phases and soil structure	40
1.1 DEFINITION AND IMPORTANCE OF GEOLOGICAL ENGINEERING	4	Saturated soils. The principle of effective stress	41
1.2 THE GEOLOGICAL ENVIRONMENT AND ITS RELATION WITH ENGINEERING	6	Seepage forces and piping	44
1.3 GEOLOGICAL FACTORS AND GEOTECHNICAL PROBLEMS	8	Loading saturated soils	50
1.4 METHODS AND APPLICATIONS IN GEOLOGICAL ENGINEERING	15	The concept of consolidation	50
1.5 INFORMATION SOURCES IN ENGINEERING GEOLOGY	16	Concepts of loading with and without drainage	51
1.6 HOW THIS BOOK IS STRUCTURED	16	Undrained loading in saturated soils	52
RECOMMENDED READING	17	2.5 CONSOLIDATION AND COMPRESSIBILITY	56
REFERENCES	17	Normally consolidated and over-consolidated soils	56
		Horizontal stresses in the ground	62
		Influence of complementary factors on soil behaviour	63
<b>2 SOIL MECHANICS AND ENGINEERING GEOLOGY OF SEDIMENTS</b>	<b>19</b>	The oedometer test	65
2.1 INTRODUCTION	20	2.6 SHEAR STRENGTH OF SOILS	71
The nature of soils	20	Failure criterion	71
Soils in geotechnical engineering	20	The direct shear test	72
2.2 SOIL DESCRIPTION AND CLASSIFICATION. PHASE RELATIONSHIPS	23	Behaviour of soils subjected to shear stress	76
Types of soils	23	Granular soils	76
Particle size distribution	23	Clay soils	78
		The triaxial test	79
		The test apparatus	79

## CONTENTS

Types of test	81	Weathering processes	125
The uniaxial compression test	85	Weathering of intact rock	126
2.7 INFLUENCE OF MINERALOGY AND FABRIC ON THE GEOTECHNICAL PROPERTIES OF SOILS	85	Weathering of rock masses	127
Clay minerals in engineering geology	86	Groundwater	129
Physico-chemical properties	88	Permeability and water flow	129
Geotechnical properties and mineralogical composition	89	Effects of water on the properties of rock masses	129
Microfabric of clayey soils	89	3.3 STRESS AND STRAIN IN ROCKS	131
Geotechnical properties and microfabric Summary	94	Force and stress	131
2.8 ENGINEERING GEOLOGICAL CHARACTERISTICS OF SEDIMENTS	94	Stress on a plane	132
Colluvial deposits	95	Stress in three dimensions	138
Alluvial deposits	95	Strength and failure	139
Lacustrine deposits	95	Basic concepts	139
Coastal deposits	95	Failure mechanisms	140
Glacial deposits	96	Stress-strain relationships in rock	141
Deserts and arid climate deposits	97	Strength criteria	144
Evaporitic deposits	98	3.4 STRENGTH AND DEFORMABILITY OF INTACT ROCK	147
Tropical soils	98	Strength and strength parameters	147
Volcanic soils	99	Effects of anisotropy and pore pressure on strength	147
2.9 PROBLEMATIC SOILS	100	Failure criteria	149
Swelling and shrinking clays	101	Mohr-Coulomb criterion	149
Dispersive soils	103	Hoek-Brown's criterion	150
Saline and aggressive soils	104	Deformability	150
Collapse soils	104	Strength and deformability laboratory tests	154
The action of ice and permafrost	106	Uniaxial compression test	154
Soft sensitive soils	106	Triaxial compression test	159
Soils susceptible to liquefaction	106	Tensile strength tests	162
RECOMMENDED READING	107	Sonic velocity	164
REFERENCES	107	Limitations of laboratory tests	164
<b>3 ROCK MECHANICS</b>	<b>109</b>	3.5 DISCONTINUITIES	165
3.1 INTRODUCTION	110	Influence on rock mass behaviour	165
Definition, objectives and scope	110	Types of discontinuities	166
Rock and soil	112	Characteristics of discontinuities	168
Rock masses	113	Shear strength of discontinuity planes	170
3.2 PHYSICAL AND MECHANICAL PROPERTIES OF ROCKS	116	Barton and Choubey criterion	172
Rock characteristics	116	Discontinuities with infilling	175
Physical properties of intact rock	118	Direct shear strength laboratory test	175
Rock classification for geotechnical purposes	122	Permeability and water pressure	177
Rock mass classification	124	3.6 STRENGTH AND DEFORMABILITY OF ROCK MASSES	179
Weathering of rock	125	Rock mass strength	179
		Failure criteria for isotropic rock masses	181
		Failure criteria for anisotropic rock masses	186

Summary	187	Pumping tests	238
Rock mass deformability	187	Injection tests	248
<i>In situ</i> deformability tests	188	Tracer tests	249
Geophysical methods	188	4.5 SOLUTION METHODS	251
Empirical correlations	189	Analytical methods	251
Permeability and water pressure	193	Flow nets	252
Scale effect	195	Numerical methods	253
3.7 <i>IN SITU</i> STRESS	201	4.6 CHEMICAL PROPERTIES OF WATER	255
Origin and types of <i>in situ</i> stress	201	Chemical quality of groundwater	255
Geological and morphological factors which influence the state of stress	203	Physical-chemical processes. Water-aquifer interaction	256
Methods for measuring <i>in situ</i> stress	205	Contamination of groundwater	257
Measuring the direction of stresses by geological methods	206	Anthropogenic activities	257
Estimating stress magnitude from empirical relationships	207	Mechanisms of ground water contamination	258
Instrumental methods for measuring orientation and magnitude of stress	207	RECOMMENDED READING AND REFERENCES	259
3.8 ROCK MASS CLASSIFICATIONS	215	<b>PART II – METHODS</b>	
RMR Classification	216	<b>5 SITE INVESTIGATION</b>	<b>263</b>
Geomechanical classifications in practice	216	5.1 <i>PLANNING AND DESIGN</i>	264
RECOMMENDED READING	220	Aims and importance	264
REFERENCES	221	Planning site investigations	264
<b>4 HYDROGEOLOGY</b>	<b>223</b>	5.2 <i>PRELIMINARY INVESTIGATIONS</i>	268
4.1 <i>HYDROGEOLOGICAL BEHAVIOUR OF SOILS AND ROCKS</i>	224	Desk-based study	268
Types of aquifers and their behaviour	224	Aerial photo and remote sensing interpretation	269
Piezometric level	227	Aerial photo interpretation	269
Water movement in aquifers	228	Remote sensing	270
4.2 <i>HYDROGEOLOGICAL PARAMETERS</i>	230	The walk-over survey	273
Porosity	230	Preliminary site investigation report	275
Storage coefficient	231	5.3 <i>ENGINEERING GEOPHYSICS</i>	275
Permeability	232	Surface geophysics	276
Transmissivity	233	Electrical methods	276
4.3 <i>FLOW, DARCY'S LAW AND FUNDAMENTAL FLOW EQUATIONS IN POROUS MEDIA</i>	233	Seismic methods	277
Darcy's law	233	Electromagnetic methods	282
Darcy's velocity and real velocity	234	Gravity methods	285
Generalization of Darcy's law	235	Magnetic methods	285
Continuity equation for steady flow	236	Borehole geophysics	286
Laplace equation	236	Geophysical logging	286
Poisson's equation	237	Seismic logging inside boreholes	287
Flow equation in transitory regime	237	Seismic tomography	288
4.4 <i>EVALUATION METHODS FOR HYDROGEOLOGICAL PARAMETERS</i>	238	5.4 <i>BOREHOLES, TRIAL PITS, TRENCHES AND SAMPLING</i>	289
		Borehole drilling	289
		Rotary drilling	289
		Auger drilling	291
		Percussion drilling	292

Special boreholes	293	Filling	342
Number and depth of boreholes	293	Seepage	343
Borehole data presentation	293	6.5 ROCK MASS PARAMETERS	343
Trial excavations	293	Number and orientation of	
Geotechnical sampling	294	discontinuity sets	344
Borehole logging	297	Block size and fracture degree	344
5.5 <i>IN SITU</i> TESTS	301	Degree of weathering	347
Standard penetration test (SPT)	301	6.6 ROCK MASS CLASSIFICATION AND	
Probing penetrometers	302	CHARACTERISATION	349
Cone penetration test (CPT)	303	RECOMMENDED READING	349
Field vane test	305	REFERENCES	350
Schmidt hammer test	305	<b>7 ENGINEERING GEOLOGICAL MAPPING</b>	<b>351</b>
Point load test	306	7.1 DEFINITION	352
Shear strength test on		7.2 TYPES OF MAPS	352
discontinuities	308	Classification	352
Tilt test	310	Content of engineering geological maps	354
Pressuremeter test	311	Classification and geotechnical	
Plate loading test on soils	311	properties of soils and rocks	354
Dilatometer test	312	Hydrogeological conditions	357
Plate loading test on rock	313	Geomorphological conditions	357
Flat jack test	313	Geodynamic processes	357
Seismic methods	316	7.3 MAPPING METHODS	358
Measuring <i>in situ</i> stress	316	Geotechnical zoning	358
Permeability tests	316	Representing data	358
Permeability tests on soils	316	Computer aided mapping	360
Permeability tests on rock	317	Geotechnical cross-sections	360
5.6 GEOTECHNICAL INSTRUMENTATION	319	7.4 DATA COLLECTION	360
Displacement measurements	319	7.5 APPLICATIONS	361
Pore pressure and water level		Land and urban planning	361
measurements	322	Engineering	361
Stress measurements	324	RECOMMENDED READING	365
RECOMMENDED READING	325	REFERENCES	365
REFERENCES	325	<b>PART III – APPLICATIONS</b>	
<b>6 ROCK MASS DESCRIPTION AND</b>		<b>8 FOUNDATIONS</b>	<b>369</b>
<b>CHARACTERISATION</b>	<b>327</b>	8.1 INTRODUCTION	370
6.1 METHODOLOGY	328	Basic design criteria	370
6.2 DESCRIPTION AND ZONING	331	Stages in foundation design	371
6.3 INTACT ROCK CHARACTERISATION	331	8.2 SHALLOW FOUNDATIONS	371
Identification	332	Types of shallow foundations	371
Weathering	332	Ultimate bearing capacity	372
Strength	332	Basic definitions	372
6.4 DESCRIPTION OF DISCONTINUITIES	335	Calculating the ultimate bearing	
Orientation	335	capacity	373
Spacing	336		
Persistence	337		
Roughness	338		
Strength of discontinuity wall	340		
Aperture	341		

Ultimate bearing capacity in undrained conditions	374	Geological structure and discontinuities	404
Ultimate bearing capacity in drained conditions	375	Hydrogeological conditions	405
Factor of safety. Safe bearing capacity	375	Geomechanical properties of soil and rock masses	408
Distribution of pressures under shallow foundations	376	<i>In situ</i> stresses	408
Stress distribution under loaded areas	378	Other factors	409
Fundamentals. Criteria for use	378	9.4 TYPES OF SLOPE FAILURE	410
Point load on an elastic half-space	379	Soil slopes	410
Vertical stresses under the corner of a uniformly loaded rectangle	379	Rock slopes	411
Stresses under a uniformly loaded circular area	380	Plane failure	411
Settlement in soils	382	Wedge failure	412
General considerations	382	Toppling	413
Immediate and consolidation settlement	382	Buckling	414
Immediate and primary consolidation settlements in saturated clays	383	Non-planar failure	414
Settlements in granular soils	384	9.5 STABILITY ANALYSIS	415
Settlements in stiff clays	384	Introduction	415
8.3 DEEP FOUNDATIONS	385	Limit equilibrium methods	415
Types of pile	386	Soil slopes	417
Single piles	387	Rock slopes	426
Ultimate load capacity of a pile	389	Stress-strain methods	432
Pile groups	391	Geomechanical slope classification	433
Negative friction on piles	391	Slope mass rating (SMR)	433
Laterally loaded piles	392	9.6 STABILIZATION MEASURES	434
8.4 FOUNDATIONS ON ROCK	392	Introduction	434
8.5 FOUNDATIONS IN COMPLEX GEOLOGICAL CONDITIONS	394	Stabilization methods	435
Expansive soils	394	Modifying the geometry	435
Collapsible soils	396	Drainage methods	436
Karstic cavities	396	Resistant structural elements	439
Volcanic cavities	396	Walls and retaining elements	440
Soft and organic soils	397	Surface protection measures	441
Anthropogenic fills	397	9.7 MONITORING AND CONTROL	443
8.6 SITE INVESTIGATION	398	9.8 SLOPE EXCAVATION	445
Stages in site investigations	398	Rippability criteria	447
RECOMMENDED READING	400	RECOMMENDED READING	449
REFERENCES	400	REFERENCES	449
<b>9 SLOPES</b>	<b>401</b>	<b>10 TUNNELS</b>	<b>451</b>
9.1 INTRODUCTION	402	10.1 INTRODUCTION	452
9.2 SITE INVESTIGATIONS	403	10.2 SITE INVESTIGATION	453
9.3 FACTORS INFLUENCING SLOPE STABILITY	404	10.3 INFLUENCE OF GEOLOGICAL CONDITIONS	454
Stratigraphy and lithology	404	Geological structure	457
		Discontinuities	458
		Intact rock strength	459
		Hydrogeological conditions	460
		<i>In situ</i> stress	461
		Methods of analysis	462
		Effects of high stress on tunnelling	464

## CONTENTS

10.4	GEOMECHANICAL DESIGN PARAMETERS	464	11.3	SITE INVESTIGATION	507
	Geological and geomechanical data	464		Planning site investigation	507
	Strength and deformability	465		Preliminary and feasibility studies	508
	Magnitude and direction of <i>in situ</i> stress	466		Selecting the type of dam	508
	Estimation of <i>K</i> from the TSI index	466		Design	508
	Sheorey's method	471		Construction	508
	Water inflow and pressure	471		Operation	509
10.5	ROCK MASS CLASSIFICATIONS FOR TUNNELLING	472	11.4	ENGINEERING GEOLOGICAL CRITERIA FOR DAM SELECTION	513
	Q System	472		General criteria	513
	SRC rock mass classification	476		Foundation conditions	513
	Suggested criteria for the application of rock mass classifications	480		Availability of materials	514
10.6	TUNNEL SUPPORT DESIGN USING ROCK MASS CLASSIFICATIONS	480		Siting of auxiliary structures	514
	Tunnel support based on RMR classification	481		Conditions for embankment dams	515
	Tunnel support based on the Q index	483		Conditions for concrete dams	515
10.7	EXCAVABILITY	483	11.5	GEOLOGICAL MATERIALS FOR DAM CONSTRUCTION	516
10.8	TUNNEL EXCAVATION AND SUPPORT METHODS IN ROCK	484		Site investigations for dam materials	516
	Excavation methods	487		Types of materials	516
	Stages of excavation	489		Cores	516
	Support systems	489		Rockfills and ripraps	517
	Ground improvement	491		Filters and drains	517
	The New Austrian Tunnelling Method	491		Aggregates	517
	Portals	492	11.6	RESERVOIR WATER TIGHTNESS	518
10.9	TUNNEL EXCAVATION AND SUPPORT METHODS IN SOIL	493	11.7	PERMEABILITY OF DAM FOUNDATIONS	519
	Non-mechanical excavation methods	493		Uplift pressures	519
	Semi-mechanical excavation methods	493		Erosion	519
	Tunnel excavation with tunnel boring machines	494		Leakage control	521
10.10	GEOLOGICAL ENGINEERING DURING TUNNEL CONSTRUCTION	495	11.8	RESERVOIR SLOPE STABILITY	521
RECOMMENDED READING		499	11.9	ENGINEERING GEOLOGICAL CONDITIONS FOR DAM FOUNDATIONS	523
REFERENCES		499		General conditions	523
<b>11 DAMS AND RESERVOIRS</b>		<b>501</b>		Loads on dam foundations	523
11.1	INTRODUCTION	502		Dam foundation failure mechanisms	524
11.2	TYPES OF DAMS AND AUXILIARY STRUCTURES	503		Stress distributions in dam foundations	527
	Types of dams	503		Foundation improvement measurements	528
	Embankment dams	504		Dam foundation problems and possible remedial measures	529
	Concrete dams	504	11.10	SEISMIC ACTIONS AND INDUCED SEISMICITY	532
	Auxiliary structures	506	RECOMMENDED READING		533
			REFERENCES		533
			<b>12 EARTH STRUCTURES</b>		<b>535</b>
			12.1	INTRODUCTION	536

12.2	DESIGN METHODOLOGY	537	Susceptibility and hazard maps	591
12.3	MATERIALS	540	Slope movement maps	591
	Earthfill embankments	540	Collapse and subsidence maps	592
	Rockfill embankments	541		
	Coarse rockfill	545	RECOMMENDED READING	593
12.4	IMPLEMENTATION AND CONTROL	545	REFERENCES	593
12.5	EMBANKMENTS ON SOFT SOILS	548	<b>14 SEISMIC HAZARD</b>	<b>595</b>
12.6	EMBANKMENTS ON SLOPES	550	14.1 INTRODUCTION	596
REFERENCES AND RECOMMENDED READING	551	14.2 FAULTS AND EARTHQUAKES	596	
		Faults as the source of earthquakes	596	
		Stick-slip regimes and the seismic cycle	597	
		The seismic fault model	598	
		Slip rates and recurrence periods	599	
		Geological recording of fault activity	600	
		The study of seismic faults	600	
<b>PART IV – GEOLOGICAL HAZARDS</b>			14.3 SEISMICITY STUDIES	604
<b>13 LANDSLIDES AND OTHER MASS MOVEMENTS</b>	<b>555</b>	14.4 SEISMIC HAZARD ANALYSIS	606	
13.1 INTRODUCTION	556	Deterministic method	606	
13.2 SLOPE MOVEMENTS	556	Probabilistic methods	608	
Types of slope movements	557	14.5 SEISMIC SITE RESPONSE	609	
Landslides	557	Design earthquake	610	
Flows	560	Seismic parameters of ground motion	610	
Rock falls	561	Modification of ground motion by local conditions	611	
Rock avalanches	562	14.6 GROUND EFFECTS INDUCED BY EARTHQUAKES	613	
Lateral displacements	562	Liquefaction potential	613	
Causes of slope movements	563	Landslides induced by earthquakes	615	
Rainfall and climatic conditions	565	Fault rupture	616	
Changes in water level	567	14.7 APPLICATIONS TO GEOLOGICAL ENGINEERING	617	
Erosion	567	Seismic hazard studies applied to site assessment	617	
Earthquakes	568	Seismic microzonation	617	
Volcanism	569	Seismic vulnerability assessment	619	
Human actions	569	RECOMMENDED READING	622	
13.3 INVESTIGATION OF LANDSLIDES	570	REFERENCES	622	
General field surveys	570	<b>15 PREVENTION OF GEOLOGICAL HAZARDS</b>	<b>625</b>	
Analysis of the processes	574	15.1 GEOLOGICAL HAZARDS	626	
Detailed investigations	576	15.2 HAZARD, RISK AND VULNERABILITY	627	
Stability analysis	580	15.3 SAFETY CRITERIA IN GEOLOGICAL ENGINEERING	631	
Monitoring	581	15.4 PREVENTION AND MITIGATION OF GEOLOGICAL HAZARDS	638	
Alarm systems	582			
13.4 CORRECTIVE MEASURES	582			
Stabilisation and protection against rock falls	583			
13.5 COLLAPSE AND SUBSIDENCE	585			
Types of movements and their causes	585			
Collapse	586			
Subsidence	587			
Investigation of the processes	587			
Corrective measures	589			
13.6 PREVENTION OF RISKS FROM MASS MOVEMENTS	589			



## CONTENTS

15.5 HAZARD AND RISK MAPS	639	<b>APPENDIX C</b>	
RECOMMENDED READING	641	SYMBOLS AND ACRONYMS	657
REFERENCES	642	<b>APPENDIX D</b>	
		LIST OF BOXES	663
<b>APPENDIX A</b>		<b>APPENDIX E</b>	
CHARTS FOR CIRCULAR AND WEDGE FAILURE ANALYSIS	643	PERMISSIONS TO REPRODUCE FIGURES AND TABLES	665
<b>APPENDIX B</b>		<b>INDEX</b>	<b>671</b>
PRESSURE UNITS CONVERSION CHART	653		