Encyclopaedia of
Geomechanics in Soil, Rock, and Environmental Engineering

Contributors | Evgenii Sharkov, Wisley Moreira Farias, Tsuyoshi Ishikawa, and Hayder Mohammed Salim Al-Maamori et al.

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Volume IV: Rock Mechanics in Civil and Environmental Engineering

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List of Abbreviations

AE	Acoustic Emission
AMS	Anisotropy of Magnetic Susceptibility
BFEM	Base Force Element Method
DRM	Detrital Remanent Magnetization
EM	Electro-Magnetic
FEM	Finite Element Method
IRR	Infra-Red Radiation
JRC	Joint Roughness Coefficients
MTS	Mechanics Test Systems
NRM	Natural Remanent Magnetization
RAC	Recycled Aggregate Concrete
REV	Representative Elementary Volume
RMR	Rock Mass Rating
RQD	Rock Quality Designation
RSRM	Remote Sensing Rock Mechanics
SP	Self Potential
SPATE	Stress Pattern Analysis by Thermal Emission
SPT	Standard Penetration Test
TIR	Thermal Infra-Red
TSA	Thermo-Elastic Stress Analysis

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Preface

Encyclopaedia of Geomechanics in Soil, Rock, and Environmental Engineering covers the basic rock mechanics principles; how to study the interactions between these principles and a discussion on the fundamentals of excavation and support and the application of these in the design of surface and underground structures. Rock mechanics is a theoretical and applied science of the mechanical behavior of rock and rock masses; compared to geology, it is that branch of mechanics concerned with the response of rock and rock masses to the force fields of their physical environment. *Rock Mechanics in Civil and Environmental Engineering* covers topics in the area of Rock Mechanics and related areas; covers recent developments in rock mechanics; shows how Rock Mechanics today has become more and more associated with, and indeed part of, construction, energy, and environmental engineering. First chapter presents a compilation of a number of in-situ stress measurements, strength and stiffness measurements, time-dependent deformation measurements, and some dynamic properties measurements of different rock formations in Southern Ontario and the neighboring regions. Second chapter reveals on remote sensing rock mechanics and earthquake thermal infrared anomalies. In third chapter, we study roughness of center profile curve on rock fracture surfaces from statistical view. The main objective of fourth chapter is to determine the correlation in between seismic velocity values with engineering parameters such as N value, rock quality, friction angle, relative density, strength (force), consistency and velocity index. Beside than that, the correlation found also extent for good estimation which is important in engineering perspective especially for tropical region country. The main purpose of fifth chapter is to provide a theory for developing a stress-dependent hydraulic conductivity tensor for fractured rock masses. In sixth chapter, mechanical behavior of 3D crack propagation and coalescence is investigated in rock-like material under uniaxial compression. The purpose of seventh chapter is to survey the base forces element method on complementary energy principle for large-scale computing problems in rock engineering problems. Last chapter describes the microfabric of sedimentary rocks related to the tectonic regime and sedimentation processes in the mobile zone. It focuses on an attempt to apply magnetic properties to tectono-sedimentology.

Contents

Chapter 1

A COMPILATION OF THE GEO-MECHANICAL PROPERTIES OF ROCKS IN SOUTHERN ONTARIO AND THE NEIGHBOURING REGIONS

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ABSTRACT

The available measurements of the geo-mechanical properties of rocks in Southern Ontario and the neighbouring regions (New York, Ohio, Michigan, Indiana, Illinois, Wisconsin, and Minnesota) are summarized and presented. These measurements were compiled from available published data in the relevant literature and also from data that were collected from major underground projects in these regions. The compiled data are presented in three categories: measured in-situ stresses in different rock formations; calculated strength, stiffness and deformation including time-dependent deformation properties; and the measured dynamic properties of intact rock specimens from different rock formations in Southern Ontario and the neighbouring regions. The data presented in this paper can be used as a resource for preliminary evaluation of the geomechanical properties of the rocks in these regions. The presented geo-mechanical properties were generally obtained from in-situ measurements and from laboratory tests that were conducted on intact rock specimens from freshly excavated rock samples. Moreover, the time-dependent deformation properties of rocks in these regions were obtained from laboratory tests that were performed on intact rock specimens submerged in water. However, the influence of drilling fluids such as bentonite slurry and synthetic polymers solution, on the geo-mechanical properties of rocks is not evident and needs to be investigated.

INTRODUCTION

The first step in the design process of underground structures in rocks is to define the strength and deformation parameters of the rock unit in addition to the initial in-situ stresses that exist at a specific depth in the hosting rock unit. During the past few decades, extensive investigations of the initial in-situ stresses in rocks of Southern Ontario and the neighbouring regions (New York, Ohio, Michigan, Indiana, Illinois, Wisconsin, and Minnesota) and their strength and deformation properties including time-dependent deformation properties were carried out. The investigations revealed that the rocks of these regions are subjected to high initial horizontal in-situ stresses that are of great influence on the deformation behaviour of these rocks with time.

The deformation of the rocks with time is known as time-dependent deformation behaviour, which was manifested as different types of distress on the existing underground structures in Southern Ontario [1]. These distresses were observed in the form of cracks in the tunnels lining at the springline, invert heave, buckling of lining concrete of canal floors, bottom heaves in quarries; and long-term movement of walls of unsupported excavations [1]. In many cases, the resulting defects can cause severe damage on underground structures that requires costly remedial and maintenance works [1].

The time-dependent deformation behaviour of rocks in Southern Ontario was extensively investigated during the past decades [2] -[9]. Considering the osmosis and diffusion as a mechanism of swelling, these investigations were mainly based on measuring the swell deformation of intact rock specimens submerged in water with variable confining pressures and variable salinity of the ambient water. However, present-day tunnel drilling technologies such as micro-tunnelling and horizontal direction drilling involve fluids such as bentonite slurry and synthetic polymers solutions during the drilling process, which may influence the strength and time-dependent deformation behaviour of rock in the vicinity of the tunnel annulus. Bearing this in mind, it is quite indispensable to investigate the influence of these drilling fluids on the strength and time-dependent deformation behaviour of rocks in this region, and that research is ongoing at Western University. However, the research preceded with a comprehensive literature review which resulted in a compilation of available properties data obtained from tests performed on the intact rock exposed only to water.

Therefore, this paper presents a compilation of a number of in-situ stress measurements, strength and stiffness measurements, time-dependent deformation measurements, and some dynamic properties measurements of different rock formations in Southern Ontario and the neighbouring regions. The objective is that the presented data serve as initial source of information for any prospective study of the geo-mechanical properties of the rocks in these specified regions. Figure 1displays the locations of the sites from where data were compiled.

SUMMARY OF COMPILED MEASUREMENTS

In-Situ Horizontal Stresses

The available published values and directions of the in-situ horizontal stresses measured at different locations in Southern Ontario and the neighbouring regions were summarized and presented in Table 1. The presented data were compiled from sites where different measuring techniques were used to evaluate the in-situ stresses at variable depths and diversity of rock formations specifically in Southern Ontario and the surrounding regions (i.e. New York, Ohio, Michigan, Indiana, Illinois, Wisconsin, and Minnesota).

Table 1. *In-Situ* stresses in rocks.

Province/State/City	Project	Rock Formation	Rock Type	Depth (m)	Horizontal Minor stress (MPa)	Horizontal Major stress (MPa)	Direction of Major Horizontal Stress	Method Used	Source of Data
Ontario/Dufferin Creek	Outcrop in Duffin Creek, Ontario	–	Shale	9.1 - 15.2	6.9	–	–	USBM	[1]
Ontario/Elliot Lake	Mine in Elliot Lake, Ontario	–	Quartzite	390.0 - 415.0	21.4 - 44.1	–	–	–	[30]
			Diabase	256	15.2 - 41.4				
Ontario/Elliot Lake	Mine in Elliot Lake, Ontario	–	Sandstone/ Quartzite	204.8 - 701.0	17.24 - 22.06	20.69 - 36.54	East	OC	[29]
Ontario/Elliot Lake	Mine in Elliot Lake, Ontario	–	Sandstone/ Quartzite	427	24.13	35.37	–	USBM	[18]
Ontario/Kincardine	Bruce Nuclear Repository Site in Kincardine, Ontario	Cobourg	limestone	670	23	44.7	N 75°E	HF	[20]
Ontario/Mississauga	Heart Lake Tunnel in Mississauga, Ontario	Georgian Bay	Shale	6.0 - 18.2	0.86 - 6.32	1.25 - 9.5	N10° - 48 °E, N2° - 86°W	USBM	[2]
Ontario/Mississauga	Outcrop in Mississauga, Ontario	–	Shale	9.1 - 15.2	7.6	–	–	–	[1]
Ontario/Niagara Falls	SABNGS No3 in Niagara Falls, Ontario	Queenston	Shale	93.9 - 123.8	8.6 - 11.3	14.3 - 17.1	–	MSP	[16]
Ontario/Ottawa	Outcrop in Ottawa, Ontario	–	–	13.7	2.6	–	–	USBM	[31]
Ontario/Port Hope	Wesleyville Generating Station, Port Hope, Ontario	Trenton	Limestone	36.6	9.7	8.0 - 13.0	N 15°w	–	[1]
Ontario/Scarborough	Tunnel in Scarborough, Ontario	–	Shale	70.1	1.59	1.69	N 90°E	USBM	[31]
Ontario/Thorold	Thorold Tunnel In Thorold, Ontario	Gasport	Shaly limestone	18.3	6.63 - 12.7	8.14 - 14.69	N 60°E	USBM	[1] [7] [32]

Ontario/Thorold	Thorold Tunnel In Thorold, Ontario	Gasport	Dolomite	12.7 - 16.19	5.23 - 12.104	6.633 - 13.0	N27° - 88°W, N62°E	USBM	[1] [7] [32]
		Gasport	Dolomitic limestone	17.26	6.682 - 6.861	6.861 - 8.99	N60° - 76°E		
		Gasport	Fossiliferous limestone	19.82	6.647	13.833	N56°E		
		Gasport	Argillaceous limestone	24.7	6.848	10.513	N60°E		
		Gasport	Limestone with shaly interbeds	74.7 - 299.5	5.23 - 12.104	6.633 - 13.0	N27°- 88°W, N62°E		
Ontario/Thorold	Thorold Tunnel in Thorold, Ontario	Gasport member of Lockport and Decew formations	Dolomite	41.7 - 53.1	5.2 - 12.7	6.6 - 13	N27° - 88°W, N62°E	USBM	[24]
			Dolomitic limestone	56.6	5.2 - 6.6	6.8 - 9.03	N76°E		
			Shaly limestone	60.0 - 61.0	11.0 - 11.2	14.69	N58° - 60°E		
			Fossiliferous limestone	65	6.63	13.8	N56°E		
			Argillaceous limestone	81	6.83	10.5	N60°E		
Ontario/Thorold	Outcrop in Thorold, Ontario	–	Dolomite	12.7 - 15.5	5.21 - 12.07	9.03 - 12.07	N 27°- W, N 88°W	OC	[13]
			Dolomitic limestone	16.2 - 17.3	6.59 - 6.66	8.14 - 8.96	N 62°E, N 76°E		
Ontario/Thorold	Outcrop in Thorold, Ontario	–	Shaly limestone	18.3 - 18.6	11.03 - 11.17	14.69	N 60°E, N 58°E	OC	[13]
			Limestone	19.8 - 24.7	6.63 - 6.83	10.48 - 13.79	N 56°E, N 60°E		
Ontario/Wawa	Mine in Wawa, Ontario	–	Granite	341.4	40	60	–	–	[22]
Ontario/Wawa	Mine in Wawa, Ontario	–	Siderite	365.8	20.06 - 34.27	21.44 - 42.47	S 47°- 63°E	D	[28]
			Tuff	478.5	27.65 - 34.06	30.0 - 47.16	S 42°- 71°W		
			Meta - diorite	573	21.51	31.58	S 18°E		
			Chert	573	16.62 - 21.37	19.93 - 38.27	S 44°W, N 4°W		
Ontario/Wawa	Mine in Wawa, Ontario	–	–	332	27.9	–	–	D	[31]
Ontario/Darlington	Darlington Generation Station, Ontario	–	Ordovician limestone	228.0 - 300.0	10.5 - 11.3	17.2 - 19.6	N 70 E ± 7°	HF	[20]

Ontario/Toronto	Darlington Intake Tunnel, Toronto, Ontario	Whitby	Shaly limestone	74.7 - 299.5	5.8	9.3	N 63°E	_	[4]
Ontario/Toronto	Heart Lake Tunnel in Toronto	Georgian Bay	Shale	6.57 - 18.20	0.80 - 6.32	1.25 - 9.50	N 10° - 48°E, N 2 - 86°W	–	[3]
Ontario/North Bay	Outcrop in North Bay, Ontario	–	–	13.7	8.3	_	_	D	[31]
Ontario/Sudbury	Tunnel in Sudbury, Ontario	–	Jasperoid	45.7	44.82	51.71	_	–	[13] [31]
Quebec/Lake Beauchene	Tunnel in Lake Beauchene, Quebec	–	Gneiss W. Mica, Quartz	64	7.58	20	N 70°W	–	[13] [34]
Quebec/Churchhill	Cavern adit in Churchhill Falls, Quebec	_	Gneissic	305	11.72	13.79	_	OC	[35]
Quebec/James Bay	Mine in James Bay, Quebec	–	Monzonite/Syenite	121.9	5.48 - 11.24	8.14 - 20.69	N 0°E	D	[31]
Manitoba	Underground Research Laboratory in Manitoba	–	Granite	336.6 - 515	31.0 - 42.0	60.0 - 83.4	_	MSP	[26] [36]
Manitoba	Underground Research Laboratory in Manitoba	–	Granite	420	45	60	_	–	[23] [37]
Manitoba	Underground Research Laboratory in Manitoba	_	Granite	470.1 - 471.5	54.5 - 62.5	57.1 - 69.3	_	_	[38]
				579.5 - 670.8	56.9 - 76.0	61.0 - 76.7			
				745	46.8 - 51.8	57.9 - 61.5			
				836.9 - 851.3	56.2 - 78.3	62.6 - 85.7			
New York/Alma Township	Oil Field-Deep Boring in Alma Township, New York	–	Sandstone	502.9	10.17	15.69	N 77°E	HF	[19]
New York/Briarcliff Manor	Outcrop in Briarcliff Manor, New York	–	Gneiss	5.6 - 13.1	_1.48 - 3.62	_0.08 - 11.39	N 0°- 90°E, N64°- 74°W	OC	[13]
New York/Clarendon	Deep Borehole in Clarendon, New York	_	Sandstone/limestone	_	_	10.24	N 64°E	USBM	[31]
New York/Dale	Deep Boring in Dale, New York	–	Sandstone	_	11.89	18.61	_	HF	[13] [39]
New York/Niagara Gorge	Outcrop in Niagara Gorge, New York	–	Dolomite	0.2 - 6.7	_0.3 - 2.28	6.0 - 6.21	N34° - 55°E	OC	[13] [40]
New York/Nyack	Outcrop in Nyack, New York	–	Diabase	0.2 - 0.5	0.47	1.19	N 2°E	OC	[13] [41]

New York/Rochester	Sewer System in Rochester, New York	_	Dolomite	7.5 - 15.4	_4.87 - 10.43	5.56 - 29.89	N10° - 86°E, N80° - 82°W	OC	[42]
New York/Somerset	Outcrop in Somerset, New York	_	Sandstone	8.5	3.17	4.41	N 15°W	OC	[13] [43] [44]
New York/Sterling	Outcrop in Sterling, New York	_	Sandstone	10.1 - 32.3	4.59 - 6.55	8.27 - 10.34	N22°- 90°W	OC	[13] [43] [44]
Illinois	Oil Field-Deep Boring in southern Illinois	_	Carbonate	99.1	2.41	7.76	N 62°E	OC	[17]
Michigan	Deep Boring in Gratiot Co., Michigan	_	Shale	5108	95	135	_	OC	[15]
			Sandstone	3660	67	90			
			Dolomite	3805	42	56			
Minnesota/Coldspring	Quarry in Coldspring, Minnesota	_	Granite	15	5.58	16.48	N 40°E	OC	[12]
Minnesota/Ely	Tunnel in Ely, Minnesota	_	Gabbro	305	10.3	16.5	_	OC	[12]
Minnesota/St. Cloud	Quarry in St. Cloud, Minnesota	_	Granite	_	10.58	15.1	N 50°E	D	[45]
Ohio	Boring in Ohio	_	Shale	10.3 - 18.6	4.69 - 32.41	5.58 - 38.13	N45° - 83°W N54° - 86°E	OC	[13]
Ohio/Barberton	Mine in Barberton, Ohio	_	Limestone	701	23.44	44.82	N 90°W	HF	[21]
Ohio/Falls Township	Oil Field-Deep Boring in Falls Township, Ohio	_	Sandstone	808	11.2	24.13	N 64°E	OC	[17]
Ohio/Hocking State Forest	Outcrop in Hocking State Forest, Ohio	_	Sandstone	0.9 - 1.2	0.37	0.63	N 61°E, N 83°E	OC	[14]
Wisconsin/Montello	Deep Boring in Montello, Wisconsin	_	Granite	75.0 - 188.1	6.2 - 8.2	14.0 - 20.0	N 63°E ± 20°	HF	[13] [46]

D: door stopper with South African CSIR strain cell, HF: hydro-fracturing technique, MSP: modified stress path method [16], OC: over coring technique; USBM: the US bureau of mines deformation meter.

In general, one of the earliest attempts to measure the in situ stresses in rocks was made by Hast in the 1950's in Scandinavia as described in [11]. This attempt was followed by numerous studies that resulted in developing several methods to measure the in-situ stresses in different locations all over the world, many of which were in Southern Ontario. The most commonly methods to measure the initial horizontal in-situ stresses in rocks are: 1) the hydraulic fracturing (hydro-frac- turing test); 2) the over-coring technique with U.S. Bureau Mines probe (USBM); and 3) the under-coring technique with electrical strain gauges affixed in the borehole under consideration.

The hydraulic fracturing test consists essentially of sealing off a section of a borehole and injecting a fluid into the interval, inducing a fracture in the surrounding rock. The orientation of the resulting fracture and the pressures required to maintain the fracture are incorporated in an analysis to determine the in-situ stresses [12] [13]. The over-coring technique with (USBM) probe consists of drilling a hole to the required depth and then, from the bottom of this hole, a pilot hole of 38 mm diameter is drilled and the (USBM) probe is fixed in that hole. Then, the pilot hole is over-cored by employing a large diameter core bit to separate the rock core cylindercontaining the probe from in-situ. Later, the rock core cylinder is removed from the ground and tested in a hydraulic chamber to determine the modulus of elasticity and to calculate the in-situ horizontal stress using elastic theory relationships [13].

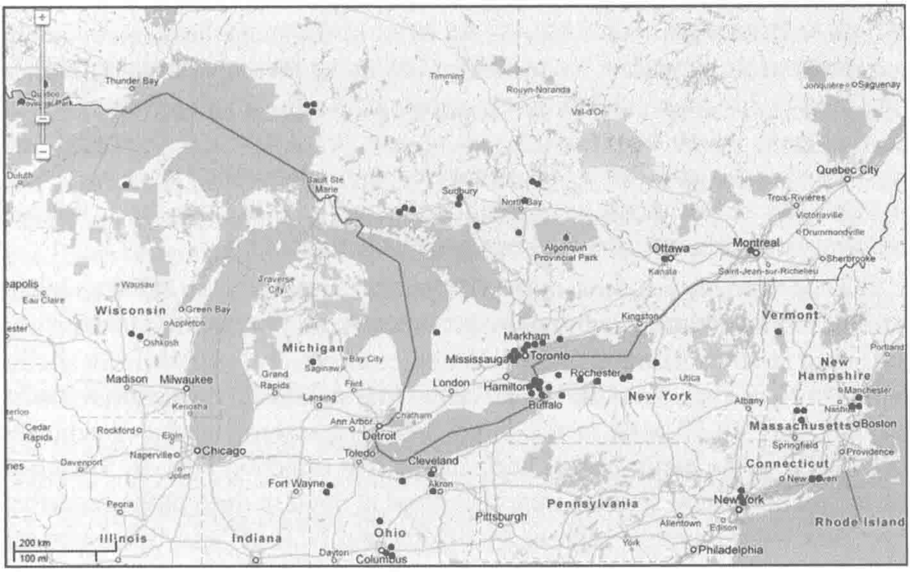

Figure 1. Locations of geo-mechanical data measurements [10].

The under-coring technique employs a package of electrical strain gauges, which is affixed to the base of the borehole. The waterproof electrical package and connections are sealed in a cylindrical form of plastic, and are affixed with quick setting epoxy at the bottom of the borehole. The deformation measurements of the borehole are taken before and after extending the core bit beyond the base of the borehole which under-cores the electrical strain gauges [13].

From the summarized data presented in Table 1, the value of the initial in-situ horizontal stress in rock formations of Southern Ontario and the neighbouring regions varies from a relatively small amount (<1 MPa) for sandstone in Ohio [13] [14] to a considerably high amount (>80 MPa) for sandstone in Michigan [15]. The high variation of the measured in-situ stress in rocks depends on the rock formation, type, depth and interbedded layers in the rock mass where stress measurements were taken. For example, the Georgian Bay shales in Toronto, Ontario possess an initial in-situ horizontal stress of a considerably high value of 1.25 - 9.5 MPa in the major horizontal