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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.

Keywords

Geo-Mechanical Properties, Rocks, Southern Ontario, Compilation

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1. 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 1** displays the locations of the sites from where data were compiled.

2. Summary of Compiled Measurements

2.1. *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). 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-fracturing 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 hy-

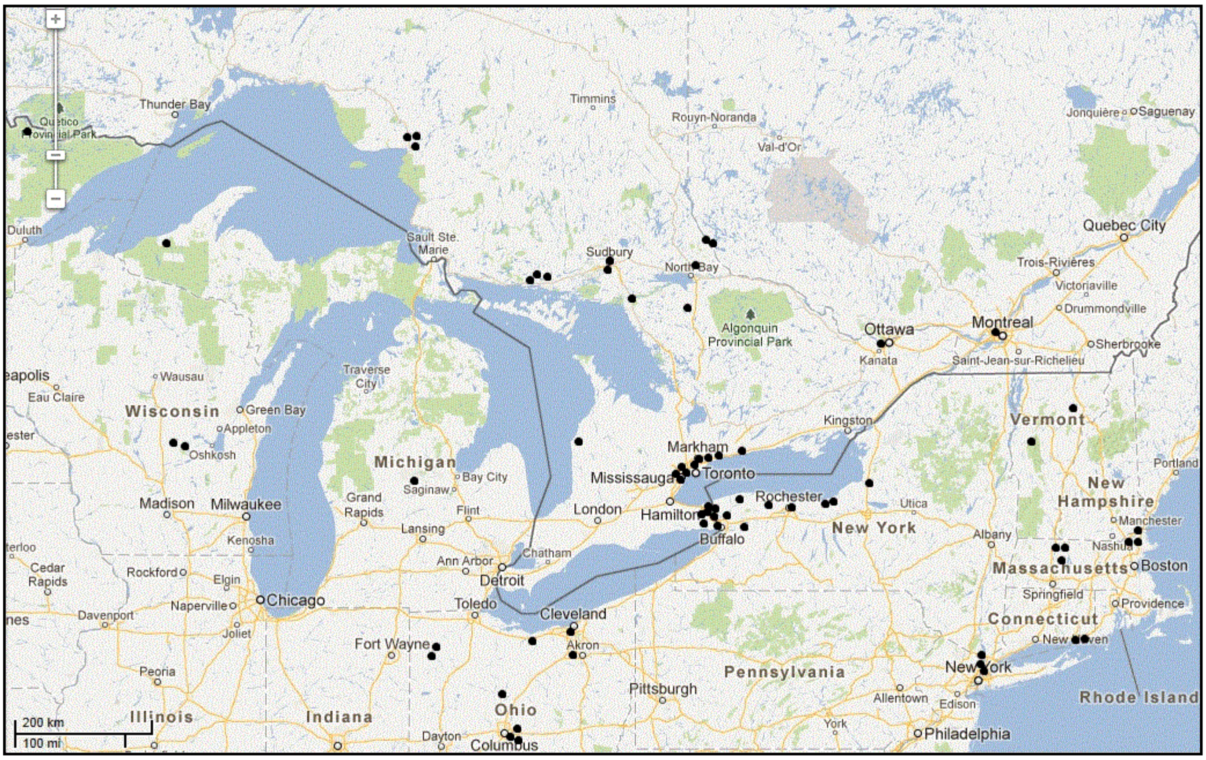

Figure 1. Locations of geo-mechanical data measurements [10].

draulic chamber to determine the modulus of elasticity and to calculate the *in-situ* horizontal stress using elastic theory relationships [13]. 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 stress direction and 0.86 - 6.32 MPa in the minor horizontal stress direction at depth of 6.0 - 18.2 m [2] [3]. The Queenston shale from the Niagara Falls area, Ontario, exhibits an initial *in-situ* horizontal stresses of 14.3 - 17.1 MPa in the major horizontal stress direction and 8.6 - 11.3 MPa in the minor horizontal stress direction at depth of 93.9 - 123.8 m [16]. In addition, shale in Ohio, at 10.3 - 18.6 m depth, possesses comparatively high *in-situ* horizontal stresses of 5.56 - 38.13 MPa and 4.69 - 32.41 MPa in the major and minor *in-situ* horizontal stress directions, respectively [13]. In the presented data, the highest measured *in-situ* horizontal stresses in shale of North America were recorded in Michigan, where the stress measurements were taken at overwhelming depths that exceeded 5100 m. The measured *in-situ* horizontal stresses in shale of Michigan at that depth were 135.0 MPa and 95.0 MPa in the major and minor *in-situ* horizontal stress directions, respectively [17].

On the other hand, sandstone of Elliot Lake, Ontario, at 427.0 m depth, exhibits an *in-situ* horizontal stress of 35.37 MPa and 24.13 MPa in the major and minor *in-situ* horizontal stress direction, respectively [18], while for similar depths in New York State the *in-situ* horizontal stresses in the sandstone were varying from 10.17 MPa in the minor *in-situ* horizontal stress direction to 15.69 MPa in the major *in-situ* horizontal stress direction [19]. In Michigan, the *in-situ* horizontal stresses were measured at 3660 m deep in the sandstone layer and were found as high as 90.0 MPa and 67.0 MPa in the major and minor *in-situ* horizontal stress directions, respectively [15].

The limestone in Kincardine, Ontario and the limestone in Barberton, Ohio exhibits considerably high *in-situ* horizontal stresses of 44.7 MPa and 23.0 MPa in the major and in the minor *in-situ* horizontal stress directions, respectively, at depths of around 700 m [20] [21]. Similarly, the measured *in-situ* horizontal stresses at 341 - 420 m depth in the granite layer in Wawa, Ontario and in Manitoba were as high as 60.0 MPa in the major *in-situ* horizontal stress direction and 40.0 MPa in the minor *in-situ* horizontal stress direction [13] [22] [23]. Although the *in-situ* vertical stresses from the overburden are not presented here in the compiled data, it could be perceived that in general, the rock formations in Ontario and neighbouring regions are subjected to a considerably high *in-situ* horizontal stresses.

Lo [1] analyzed natural geological features, such as: faulting; folding and buckling or pop-up of surface rock strata; distress in shallow and deep excavation, such as heaves in the Dufferin quarry in Milton; jamming of wheel pit, bending and buckling of steel beams structures of hydro-electric power plants; and crushing and spalling of arch and floor heave of the hydro tunnels in the Niagara area and Chippawa Canal in Ontario. Based on these analyses, it was suggested by Lo [1] that these observations were evidence of high *in-situ* horizontal stresses that resulted from the current movement of continental drift according to tectonic theory, and not due to the past overburden load during glaciation ages [1]. From the recorded *in-situ* stress measurements and the observation of natural phenomena, it was proposed that the belt of high horizontal stresses stretches from Rochester in New York State westward through Niagara Falls, turning northeast around Lake Ontario following the lake shore line and extending at least as far east as Wesleyville, Ontario [1].

The high *in-situ* horizontal stresses in rocks are a general phenomenon that exists in many regions in North America and the world. However, the rock formations in Southern Ontario and the neighbouring states, in specific, exhibit a considerably high *in-situ* horizontal stresses. These high *in-situ* horizontal stresses, after their relief, might be of significant influence on the time-dependent deformation characteristics of these rocks, which in turn might cause serious damages to the constructed underground structures.

2.2. Intact Rock Strength and Stiffness Properties

The values of the tensile strength, compressive strength, elastic (Young's) modulus and Poisson's ratio of different rock formations in Southern Ontario and the neighbouring regions are summarized and presented in **Table 2**. The presented data were compiled from available relevant literature.

The tensile strength of intact rock is measured in a laboratory either directly with the direct tension test or indirectly with the indirect tension test, which is commonly known as a Brazilian test or a split test. In the direct tension test, a cylindrical rock specimen is subjected to a direct uniaxial tensile stress along its longitudinal axis until failure. In the Brazilian test, the indirect tensile strength of the rock is measured on disc specimens by applying a compressive stress across the disc perimeter until failure. The failure occurs along the diameter of the disc specimen in a biaxial state of stress where one principal stress is highly compressive. In general, the indirect tensile strength of rock measured from the Brazilian test is higher than the tensile strength of the same rock measured from the direct tension test.

The compressive strength, elastic (Young's) modulus, and Poisson's ratio of intact rocks are all measured in a laboratory either through a uniaxial compression test or a triaxial compression test. In the uniaxial compression test, a cylindrical rock specimen is subjected to a compressive stress along its longitudinal axis until failure occurs, while in the triaxial compression test, failure is similarly induced when the cylindrical rock specimen is subjected to a specific value of confining pressure. In both tests, electronic strain gauges are affixed onto the specimen, parallel and perpendicular to the longitudinal axis of the specimen, to measure the axial and diametric deformations during the tests. The elastic theory relationships are then used to calculate the elastic modulus and Poisson's ratio.

The strength and stiffness characteristics of intact rock specimens extracted from different rock formations in Southern Ontario and the neighbouring regions were extensively investigated over the past decades [4] [18] [24]-[26]. However, the *in-situ* medium (*i.e.* the rock mass) comprises of intact rock blocks that are separated by discontinuities such as joints, fissures and faults [27]. These discontinuities have a great influence on the overall strength characteristics of the rock mass, and therefore they have to be prudently considered in evaluating the overall strength of the rock mass. The rock mass modulus can be measured *in-situ* by recording the deformation in the diameter of a pre-drilled monitoring hole through the rock mass while extending the tunnel excavations.

The deformation is recorded using an extensometer probe that is affixed at the bottom of the monitoring hole. Another field test method was developed in 1987 by Lo, Yung and Lukajic [25] to measure the rock mass modulus at the surface of the excavated rock. In principle, the developed method consisted of measuring the variation in the diametric distance between each opposite pair of pre-glued props into pre-drilled holes from the surface of the rock layer, in a rosette pattern, while extending a central hole into the rock layer from the surface. The elastic theory was then used to calculate the rock mass modulus [25]. The developed method was used to measure the rock mass modulus of the limestone layer at the intake and discharge tunnels of Darlington Generating Station, east of Toronto. The values of the measure rock modulus from this method were consistent with those evaluated from extensometer measurements in the tunnels.

As mentioned before, the strength data presented in **Table 2** were assembled from laboratory tests performed on intact rock specimens of samples extracted from variable depths and diversity of rock formations in the concerned area. In general, the dolomitic limestone of Lockport formation possesses the highest uniaxial compression strength of 199 - 246 MPa among all other rocks in Southern Ontario [5]. The sandstone of Whirlpool formation and the dolostone of Lockport formation exhibit uniaxial compression strength of 190 MPa and 200 MPa, respectively [3]. The black shale of Collingwood formation and the Rochester shale exhibit a high uniaxial compression strength of 80 - 85 MPa in contrast to other shales in Southern Ontario, such as Georgian Bay, Grimsby, Power Glen, Blue Mountain, and Queenston in which the uniaxial compression strength ranges between 20 - 30 MPa [3]. Moreover, most of the sedimentary rocks of Southern Ontario possess anisotropy in their uniaxial compression strength, with respect to the bedding planes.

As can be seen from **Table 2**, the available data of the tensile strength of rocks in the specified area are very limited. However, it is reported that the tensile strength of Queenston shale from different sites in Southern Ontario varies between 1MPa to 15 MPa in contrast to Sherman Fall shale where the tensile strength is 0.1 - 3 MPa [20]. It is reported that the dolostone and mudstone of De Cew formation possess a tensile strength of 5 MPa [20].

The elastic modulus of siderite and tuff in Wawa, Ontario was reported as 67.6 - 118.0 GPa and 68.3 - 115.8 GPa [28], respectively. The quartzite and sandstone of Elliot Lake, Ontario possess an elastic modulus of 80.0 GPa and 76.0 GPa respectively [18] [29], while the shales, in general, possess an average elastic modulus of 10.0 GPa [2]-[4] [7] [8] [20]. On the other hand, the Poisson's ratio of rocks in Southern Ontario was ranging from 0.13 for Georgian Bay shale [5] to 0.6 for argillaceous limestone of Cobourg formation [20]. Moreover, most of the sedimentary rocks of Southern Ontario possess anisotropy in their strength and stiffness properties, with respect to the bedding planes.

As stated earlier, the presented data in **Table 2** are based on laboratory tests that were performed on freshly recovered intact rocks from the ground. In practice, the rocks at the surfaces of the underground tunnel excavations are actually exposed either to water or other drilling fluids, such as bentonite slurry or synthetic polymers solutions as part of the construction process for the buried infrastructures. These drilling fluids are used as lubricant to facilitate the drilling process through the rock mass or to convey the excavated rocks. As mentioned before, there is lack of information with regard to the influence of the exposure of rocks to the drilling fluids near the surfaces of excavation on the strength characteristics of these rocks, therefore, the influence of these drilling fluids on the strength and stiffness characteristics of rocks in Southern Ontario is under ongoing investigation at Western University.

2.3. Intact Rock Time-Dependent Deformation Properties

The swelling potential of rocks is an important factor in designing underground structures and has a significant influence on the stability of these structures. As proposed by Lo, Palmer and Quigly [7], the swelling potential in the swelling rocks can be defined as the swelling strain per log cycle of time and it can be calculated through the free swell test. In the free swell test, the intact rock specimen is submerged in water and allowed to expand freely in all directions while the swelling strain is measured in three orthogonal directions [7]. The horizontal swell strain is measured in the direction parallel to the bedding planes of the rock sample, while the vertical swell strain is measured in the direction perpendicular to the bedding planes. The swelling potential values measured in the vertical and horizontal directions with respect to the bedding planes of different rock formations in Southern Ontario and the neighbouring regions are presented in **Table 2**.

As can be seen in **Table 2**, most of the shaly rock formations exhibit anisotropy in their swelling behaviour in the direction parallel and perpendicular to the bedding planes [6]-[8]. For example, the Queenston shale from Niagara Falls exhibits swelling potential of 0.37% - 0.54% in the vertical direction and 0.22% - 0.34% in the horizontal direction [6]. The Georgian Bay shale from different sites in Southern Ontario indicates swelling potential of 0.2% - 0.22% in the vertical direction and 0.03% - 0.14% in the horizontal direction [7]. The Rochester shale exhibits relatively small swelling potential averaging 0.16% and 0.07% in the vertical and horizontal directions, respectively [7]. In general, the limestone displays zero swelling potential due to their high calcite content, however, some shaly limestone such as Gasport shaly limestone exhibits swelling potential of 0.08% in both horizontal and vertical directions [7].

Lee and Lo [8] investigated the swelling mechanism of shales in Southern Ontario by submerging the shale specimens in water with varying salt concentrations. Based on the results of their investigations, they suggested that the swelling mechanism of shales in this region was based on the process of osmosis and diffusion which occurred between the rock pore water and the ambient fluid. It was concluded that swelling occurs if three conditions are met: *i*) relief of initial stress, *ii*) accessibility of water and *iii*) an outward salt concentration gradient from pore fluid exists. They assumed that swelling may or may not occur if only one or two of these conditions are met. Although the swelling behaviour of shales in Southern Ontario was extensively investigated in water [3] [6]-[8], there is lack of information with respect to swelling behaviour of these shales in drilling fluids, such as bentonite slurry and synthetic polymers solutions.

2.4. Dynamic Properties of Rocks

The compressional wave velocity, shear wave velocity, dynamic Poisson's ratio and dynamic modulus of different rock formations in Southern Ontario were compiled and presented in **Table 3**. The compressional wave and the shear wave velocities were measured on intact rock specimens and the dynamic Poisson's ratio and the dynamic modulus were calculated using the fundamental equations for torsional vibration [5] [6] [25].

In general, the presented data revealed anisotropy in the dynamic behaviour of the sedimentary rocks in Southern Ontario. For the same rock formation, the value of the dynamic modulus in the direction parallel to the bedding planes is higher than that in the direction perpendicular to the bedding planes. It should be noted that the presented dynamic properties are obtained for intact rock specimens. However, the effects of saturation in drilling fluids such as bentonite slurry and synthetic polymers solution on the dynamic properties of rocks still need to be investigated.

3. Summary and Conclusions

A comprehensive review of the available literature on the geo-mechanical properties of rock formations in Southern Ontario and the neighbouring regions (New York, Pennsylvania, Ohio, Michigan, Indiana, Illinois, Wisconsin, and Minnesota) was performed. The available data on the measured *in-situ* stresses and the direction of major principal stress, strength and stiffness properties, time-dependent deformation properties, and dynamic properties of different rocks from that literature were compiled. The presented data can serve as a preliminary source of information for any prospective study of the geo-mechanical properties of the rocks in Southern Ontario and the neighbouring regions.

From this compiled data, the following conclusions can be drawn:

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, to a considerably high amount, >100 MPa, depending on the rock formation, depth and inter-bedded layers in the rock mass. For depths up to 30 m where most of the engineering projects are located, the *in-situ* horizontal stresses in rocks of Southern Ontario and the neighbouring regions are ranging between −4.87 MPa to 38.13 MPa, while for depths greater than 30 m and up to 1000 m where the mining projects are located, the *in-situ* horizontal stresses are ranging between 1.59 MPa to 85.7 MPa. Moreover, the *in-situ* horizontal stresses are considerably high for depths greater than 1000 m where the hydrocarbons projects are located, ranging from 42.0 MPa to as high as 135.0 MPa.
2) Among shales of Southern Ontario and the neighbouring regions, the Queenston shale of Niagara Falls region exhibits highest swelling potential of 0.37% - 0.54% in the vertical direction and 0.22% - 0.34% in the horizontal direction, with respect to the bedding planes.
3) The sedimentary rocks and shales in particular, possess considerable anisotropy in their strength, time-dependent deformation and dynamic properties, relative to the bedding planes.

4) Although the swelling behaviour of rocks in Southern Ontario and the neighboring regions was extensively investigated using water as an ambient solution, there is a lack of information with respect to the time-dependent deformation behaviour of these rocks in fluids such as bentonite slurry and synthetic polymers solution. For most of the tunnel drilling process through the rock mass, other than blasting, fluids such as bentonite slurry and synthetic polymers solutions are used either to convey the excavated materials or to lubricate the annulus of the excavated tunnel. Therefore, it is quite indispensable to investigate the influence of these fluids on the strength, time-dependent deformation and dynamic characteristics of these rocks, which is the topic of the ongoing research at Western University.

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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]

Continued

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]

Continued

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]

Continued

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.,	_	Shale	5108	95	135	_	OC	[15]
	Michigan		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.

Table 2. Intact rock strength and deformation properties.

Province/ State/City	Project	Rock Formation	Rock Type	Depth/ Elevation (m)	Tensile Strength (MPa)	Uniaxial Compressive Strength UCS (MPa)	Elastic Modulus E (GPa)	Poisson's Ratio ν	Swelling Potential (%)	Source of Data
Ontario/ Elliot Lake	Mine	_	Quartzite	390	_	31.0 - 44.1	80.0	_	_	[18]
Ontario/ Elliot Lake	Mine	_	Sandstone/ Quartzite	204.8 - 701.0	_	_	76.0	_	_	[29]
Ontario/ Elliot Lake	Mine	_	Quartzite	390 - 415	_	_	80.0	_	_	[30]
		_	Diabase	256	_	_	93.0	_	_	
Ontario/ Kincardine	Typical Values From Different Sites In Southern Ontario For The Bruce Nuclear Site	Lockport Goat Island	Dolostone	_	_	137.0 - 282.0	58.0 - 81.0	0.2 - 0.4	0.0 *h*	[8] [20]
		Lockport Gasport	Shaly limestone	_	_	27.0 - 255.0	25.0 - 70.0	0.1 - 0.5	0.08 *h*	
		De Cew	Dolostone/ Mudstone	_	5	74.0 - 174.0	43.0 - 57.0	0.3 - 0.4	0.04 *h*	
		Irondequoit	_	_	_	60.0 - 185.0	50.0 - 78.0	0.1 - 0.5	_	
		Reynales	_	_	_	53.0 - 141.0	22.0 - 49.0	0.2 - 0.5	_	
		Cabot Head	_	_	5.0 - 14.0	20.0 - 127.0	_	_	_	
		Queenston	Shale	_	1.0 - 15.0	12.0 - 118.0	7.0 - 34.0	0.1 - 0.5	0.3 *h*	
		Georgian Bay	Shale	_	_	3.0 - 206.0	1.0 - 58.0	0.1 - 0.5	0.15 *h*	
Ontario/ Kincardine	Typical Values From Different Sites In Southern Ontario For The Bruce Nuclear Site	Cobourg	_	_	_	22.0 - 140.0	10.0 - 67.0	0.1 - 0.6	_	[8] [20]
		Lockport Eramosa	Dolostone	_	_	118.0	63.0	0.4	0.0 *h*	
		Rochester	Shale	_	_	85.0	23.0	_	0.07 *h*	
		Grimsby	Sandstone/ Shale	_	_	25.0	8.0	_	0.27 *h*	
		Power Glen	Sandstone/ Shale	_	_	26.0	9.0	_	0.17 *h*	
		Blue Mountain	Shale	_	_	27.0	2.0	_	0.15 *h*	
		Collingwood	Black shale	_	_	80.0	20.0	_	0.0 *h*	
			Grey mudstone	_	_	58.0	10.0	_	0.15 *h*	
		Lindsay	Limestone with shaly interbeds	_	_	110.0	46.0	_	0.05 *h*	
		Verulam	Shaly limestone	_	_	23.0	57.0	_	0.05 *h*	
		Gull River	Limestone	_	_	143.0	63.0	_	0.0 *h*	
		Precambrian	Medium grained	_	_	190.0	60.0	_	0.0 *h*	
Ontario/ Kincardine	Typical values from different sites in Southern Ontario for the Bruce nuclear site	Granitic Gneiss	Coarse grained	_	_	140	46	_	0.0 *h*	[8] [20]
		Amherstburg	Dolostone	_	_	33.0 - 113.0	8.0 - 40.0	_	_	
			Limestone	_	_	23.0 - 182.0	12.0 - 66.0	_	_	
Ontario/ Mississauga	Heart Lake tunnel	Georgian Bay	Shale	6.0 - 18.2	_	_	12.4	0.15	_	[2]

Continued

Ontario/ Niagara Falls	Sir Adam Beck Niagara generating station (SABNGS) No. 3	Queenston	Shale	95.64 - 114.33	_	_	_	_	0.22 - 0.34 *h* 0.37 - 0.54 *v*	[6] [8]
Southern Ontario	Different Sites In Southern Ontario	Rochester	Interbedded shale and Dolomite	_	_	20.0 - 40.0	20.0	_	_	[1]
		Georgian Bay	Interbedded shale/Siltstone/ Mudstone/ Limestone	_	_	30.0 - 190.0	20.0 - 40.0	_	_	
		Collingwood	Interbedded shale/Mudstone	_	_	20.0 - 70.0	7.0 - 20.0 *v* 14.0 - 35.0 *h*	_	_	
Ontario/ Sudbury	Tunnel	_	Jasperoid	45.7	_	_	83.0	_	_	[13] [33]
Ontario/ Thorold	Outcrop	–	Dolomite	12.7 - 15.5	_	_	71.0 - 73.0	_	_	[13]
			Dolomitic limestone	16.2 - 17.3	_	_	73.0 - 74.0	_	_	
			Shaly limestone	18.3 - 18.6	_	_	43.0	_	_	
			limestone	19.8 - 24.7	_	_	55.0	_	_	
Ontario/ Thorold	Thorold tunnel	Gasport member of Lockport/De Cew formations	Dolomite	12.7 - 53.1	_	_	71.0 - 73.0	0.27 - 0.3	_	[24]
			Dolomitic limestone	56.6	_	_	74.0	o.3	_	
			Shaly limestone	60.0 - 61.0	_	_	43.0	0.25	_	
			Fossiliferous limestone	65.0	_	_	55.0	0.3	_	
			Argillaceous limestone	81.0	_	_	55.0	0.3	_	
Ontario/ Toronto	Darlington intake tunnel	Whitby	Shaly limestone	83.4	_	52.0 - 63.3 *h*	52.9 - 54.6 *h*	0.25 - 0.27 *h*	_	[25] [47]
				84.4 - 84.7	_	87.6 - 88.2 *v*	39.6 - 43.6 *v*	0.34 - 0.37 *v*	_	
Ontario/ Toronto	Domed stadium	Georgian Bay	Shale	19.8 - 26.3	_	11.2 - 17.2	2.2	0.3	_	[4]
Ontario/ Wawa	Mine	–	Siderite	365.8	_	_	67.6 - 118.0	_	_	[28]
			Tuff	478.5	_	_	68.3 - 115.8	_	_	
			Meta - diorite	573.0	_	_	52.4 - 70.3	_	_	
			Chert	573.0	_	_	51.7 - 80.0	_	_	
Southern Ontario	Research program for the National Research Council of Canada, different sites in Southern Ontario	Lockport	Dolomitic limestone	157.0 - 168.0	_	180.0 *h*	76.0 *h*	0.14 - 0.33	0.02 *h*	[7]
					_	200.0 *v*	67.0 *v*	_	0.01 *v*	
			Gasport shaly limestone	–	_	105.0 *h*	44.0 *h*	_	0.08 *h*	
					_	120.0 *v*	27.0 *v*	_	0.08 *v*	
		Rochester	Shale	26.2 - 26.52	_	70.0 *h*	27.0 *h*	_	0.07 *h* 0.16 *v*	
		Georgian Bay	Shale	10.17 - 15.33	_	35.0 *h*	21.0 *h*	0.06 - 0.25	0.03 - 0.14 *h* 0.2 - 0.22 *v*	
		Collingwood	Grey Mudstone	17.0 - 24.64	_	35.0 *h* 60.0 *v*	23.0 *h* 10.0 *v*	0.2	0.15 *h* 0.45 *v*	
			Black shale	17.0 - 24.64	_	70.0 *h* 80.0 *v*	37.0 *h* 20.0 *v*	0.1 - 0.25	0.0 *h* 0.0 *v*	

Continued

Southern Ontario	Research program for the National Research Council of Canada, different sites in Southern Ontario	Trenton-Black River	Limestone	12.9 - 35.5	_	130.0 *h* 75.0 *v*	55.0 *h* 55.0 *v*	0.19 - 0.4	0.0 *h* 0.0 *v*	[7]
			Shaly limestone	12.9 - 35.5	_	100.0 *h*	57.0 *h*	_	0.06 *h* 0.09 *v*	
		Queenston	Shale	_	_	_	_	_	0.04 *h* 0.14 *v*	
Southern Ontario	Research program for the National Research Council of Canada, different sites in Southern Ontario	Lockport	Shaly limestone (Gasport)	159.94 - 162.05	_	124.0 - 212.0 *v* 27.0 - 115.0 *h*	25.3 - 61.2 *v* 47.8 *h*	0.14 - 0.29 *v* 0.24 *h*	_	[5]
		Lockport	Fossiliferous limestone (Gasport)	159.23	_	152.0 *v*	59.1 *v*	0.24 *v*	_	
				157.33	_	102.0 *h*	75.9 *h*	0.33 *h*		
		Georgian Bay	Shale	15.33	_	35.0 *v*	5.5 *v*	0.13 *v*	_	
				10.17	_	41.0 *h*	12.1 *h*	0.06 - 0.25 *h*	_	
		Collingwood	Black Shale	22.76	_	80.0 *v*	20.4 *v*	0.18 *v*	_	
				18.49	_	25.0 - 72.0 *h*	14.8 - 38.0 *h*	0.10 - 0.15 *h*	_	
				16.99	_	21.0 *i*	13.4 *i*	0.09 *i*	_	
Southern Ontario	Research program for the National Research Council of Canada, different sites in Southern Ontario	Collingwood	Grey Shale	23.34	_	58.0 *v*	9.8 *v*	0.2 *v*	_	[5]
				23.28	_	32.0 - 35.0 *h*	19.7 - 26.0 *h*	0.09 - 0.15 *h*	_	
		Trenton	Shaly limestone	12.93 - 26.06	_	84.0 - 129.0 *h*	53.4 - 60.5 *h*	0.19 - 0.39 *h*	_	
		Trenton	Limestone	35.41	_	75.0 *v*	54.8 *v*	0.35 *v*	_	
				35.48	_	133.0 *h*	54.8 *h*	0.24 - 0.4 *h*	_	
				35.53	_	91.0 *i*	45.7 *i*	0.35 *i*	_	
		Rochester	Shale	26.37	_	85.0 *v*	22.5 *v*	0.16 *v*	_	
				26.24 - 26.52	_	61.0 - 85.0 *h*	21.8 - 32.3 *h*	0.24 - 0.26 *h*	_	
				26.29	_	40.0 *i*	19.0 *i*	0.39 *i*	_	
		Lockport	Dolomite (Goat Island)	168.17	_	246.0 *v*	64.0 *v*	0.29 *v*	_	
				168.1	_	207.0 *h*	63.3 *h*	0.31 *h*	_	
		Lockport	Dolomitic limestone (Gasport)	165.15	_	208.0 *v*	57.7 *v*	0.32 *v*	_	
Southern Ontario	Research program for the National Research Council of Canada, different sites in Southern Ontario	Lockport	Dolomitic limestone (Gasport)	165.07	_	46.0 *h*	_	_	_	[5]
		Lockport	Dolomitic limestone/ Limestone (Gasport)	163.86	_	199.0 *v*	61.2 *v*	0.25 *v*	_	
				163.78	_	191.0 *h*	63.3 *h*	0.28 *h*	_	
Southern Ontario	Thorold tunnel, wheel pits in the Canadian Niagara falls and Toronto power g.s., heart lake tunnel in Mississauga, intake tunnel of Darlington g.s., Scotia plaza in Mississauga and domed stadium in Toronto	Lockport (Eramosa)	Dolostone	_	_	120.0	63.0	_	0.0 *h*	[3]
		Lockport (Goat Island)	Dolostone	_	_	200.0	62.0	_	0.0 *h*	
		Lockport (Gasport)	Shaly Limestone	_	_	120.0	27.0	_	0.08 *h*	
		De Cew	Dolostone/ Mudstone	_	_	74.0	57.0	_	0.04 *h*	
		Rochester	Shale	_	_	85.0	23.0	_	0.07 *h*	
		Irondequoit	Limestone	_	_	90.0	60.0	_	_	
		Reynolds	Dolostone	_	_	106.0	40.0	_	_	
		Grimsby	Sandstone	_	_	132.0	42.0	_	_	
			Shale	_	_	25.0	8.0	_	0.27 *h*	

Continued

Southern Ontario	Thorold tunnel, wheel pits in the Canadian Niagara falls and Toronto power g.s., heart lake tunnel in Mississauga, intake tunnel of Darlington g.s., Scotia plaza inMississauga and domed stadium in Toronto	Power Glen	Sandstone	_	_	158.0	52.0	_	_	[3]
			Shale	_	_	26.0	9.0	_	0.17 *h*	
		Whirlpool	Sandstone	_	_	190.0	55.0	_	_	
		Queenston	Shale	_	_	30.0	10.0	_	0.30 *h*	
		Georgian Bay	Shale	_	_	20.0	4.0	_	0.15 *h*	
		Blue Mountain	Shale	_	_	27.0	2.0	_	0.15 *h*	
		Collingwood	Black shale	_	_	80.0	20.0	_	0.00 *h*	
			Grey mudstone	_	_	58.0	10.0	_	0.15 *h*	
		Lindsay	Shaly limestone	_	_	110.0	46.0	_	0.05 *h*	
		Verulam	Limestone (Shaly interbeds)	_	_	23.0	57.0	_	0.05 *h*	
		Bobcaygeon	Shaly limestone	_	_	78.0	56.0	_	_	
		Gull River	Limestone	_	_	143.0	63.0	_	0.00 *h*	
Southern Ontario	Thorold tunnel, wheel pits in the Canadian Niagara falls and Toronto power g.s., heart lake tunnel in Mississauga, intake tunnel of Darlington g.s., Scotia plaza in Mississauga and domed stadium in Toronto	Shadow Lake	Sandstone	_	_	60.0	21.0	_	_	[3]
		Pre Cambrian	Medium grained	_	_	190.0	60.0	_	0.00 *h*	
		Granitic	Coarse grained	_	_	140.0	46.0	_	0.00 *h*	
		Gneiss	Gneiss bands	_	_	90.0	46.0	_	_	
Southern Ontario	Mississauga, Pickering, Bowmanville, Wesleyville and Port Hope In Ontario	Cobourg	Argillaceous Limestone	_	0.04 - 2.0 *d* 3.0 - 10.0 *b*	22.0 - 140.0	10.0 - 67.0	0.1 - 0.6	_	[20]
			Collingwood shale	_	_	27.0 - 132.0	2.0 - 31.0	0.2 - 0.3	_	
		Sherman Fall	Shale	_	0.1 - 3.0 *d* 1.0 - 12.0 *b*	23.0 - 69.0	1.0 - 73.0	0.1 - 0.4	_	
			Interbedded limestone	_	0.1 - 3.0 *d* 1.0 - 12.0 *b*	71.0 - 161.0	1.0 - 73.0	0.1 - 0.4	_	
		Kirkfield and Coboconk	_	_	_	34.0 - 115.0	13.0 - 64.0	_	_	
Quebec/ Beauchene	Tunnel In Lake Beauchene, Quebec	_	Gneiss W. Mica/Quartz	64.0	_	_	34.5	_	_	[13] [34]
Quebec/ Churchhill falls	Cavern adit in Churchhill falls	_	Gneissic	305.0	_	_	48.0	_	_	[35]
Manitoba/ Pinawa	Underground research laboratory (URL)	_	Granite	336.6 - 515.0	_	167.0	_	_	_	[9] [26]
Manitoba/ Pinawa		_	Granite	470.1 - 851.3	_	_	15.6 - 25.8	_	_	[38]
Southern Illinois	Oil field-deep boring	_	Carbonate	99.1	_	_	14.0	_	_	[17]
Minnesota/ St. Cloud	Quarry	_	Granite	_	_	_	47.0	_	_	[45]
New York/Alma Township	Oil field-deep boring	_	Sandstone	502.9	_	_	7.0	_	_	[19]
New York/Briarcliff Manor	Outcrop	_	Gneiss	5.6 - 13.1	_	_	3.0 - 52.0	_	_	[13]
New York/Nyack	Outcrop	_	Diabase	0.2 - 0.5	_	_	19.6	_	_	[41]

Continued

New York/Niagara gorge	Outcrop	_	Dolomite	0.2 - 6.7	_	_	24.0	_	_	[13] [40]
New York/Rochester	Sewer system	_	Dolomite	_	_	_	50.7 - 91.7	_	_	[42]
New York/Somerset	Outcrop	_	Sandstone	8.5	_	_	17.0	_	_	[13] [43] [44]
New York/ Sterling	Outcrop	_	Sandstone	10.1 - 32.3	_	_	33.0	_	_	[13] [43] [44]
Ohio	Boring	_	Shale	10.3 - 18.6	_	_	13.0 - 28.0	_	_	[13]
Ohio/Barberton	Mine	_	Limestone	701.0	_	_	55.0 - 67.0	_	_	[21]
Ohio/Bellefontaine	Quarry	Gasport	Limestone/ Dolomite	0.2 - 1.0	_	_	34.8	_	_	[13]
Ohio/Falls Township	Oil Field - Deep boring	_	Sandstone	808.0	_	_	10.0	_	_	[17]
Ohio/Hocking State Forest	Outcrop	_	Sandstone	0.9 - 1.2	_	_	7.8	_	_	[14]
Ohio/Kenton	Quarry	_	Limestone/ Dolomite	0.2 - 1.0	_	_	34.8	_	_	[13]
Ohio/Lima	Quarry	_	Limestone/ Dolomite	0.2 - 1.0	_	_	34.8	_	_	[13]
Ohio/ Sydney	Quarry	_	Limestone/ Dolomite	0.2 - 1.0	_	_	34.8	_	_	[13]
Wisconsin/ Montello	Deep Boring	_	Granite	75.0 - 188.1	_	_	52.0 - 56.0	_	_	[46]

d: result from direct tension test; *b*: results from Brazilian test; *v*: results from vertically cored samples/or measurements in the vertical direction; *h*: results from horizontally cored samples/or measurements in the horizontal direction ; *i*: results from inclined 45˚cored samples with respect to the bedding planes.

Table 3. Dynamic properties of intact rocks.

Province/ State/City	Project	Rock Formation	Rock Type	Depth/ Elevation (m)	Mass Density (Mg/m³)	Compressive Wave Velocity (Km/s)	Shear Wave Velocity (Km/s)	Dynamic Poisson's Ratio vdy.	Dynamic Modulus Edy. (GPa)	Source of Data
Southern Ontario	Research Program For The National Research Council of Canada, Different Sites in Southern Ontario	Lockport (Gasport)	Shaly limestone	159.94	2.68 - 2.69 *v*	_	_	_	44.3 - 67.5 *v*	[5]
				162.05	2.68 - 2.76 *h*	_	_	_	63.3 - 71.0 *h*	
		Lockport (Gasport)	Fossiliferous limestone	159.23	2.71 *v*	_	_	_	66.8 *v*	
				157.33	2.72 *h*	_	_	_	73.1 *h*	
		Georgian Bay	Shale	15.33	2.55 *v*	_	_	_	19.2 *v*	
				10.17	2.60 *h*	_	_	_	38.2 *h*	
				12.1	2.54 *i*	_	_	_	19.0 *i*	
		Collingwood	Black shale	22.76	2.53 *v*	_	_	_	27.4 *v*	
				18.49	2.53 - 2.56 *h*	_	_	_	51.3 - 58.4 *h*	
				16.99	2.58 *i*	_	_	_	37.3 *i*	
		Collingwood	Grey shale	23.34	2.6 *v*	_	_	_	4.9 *v*	
				23.27	2.61 - 2.64 *h*	_	_	_	42.2 - 49.2 *h*	
Southern Ontario	Research Program For The National Research Council of Canada, Different Sites in Southern Ontario	Collingwood	Grey shale	23.29	2.6 *i*	_	_	_	_	[5]
		Collingwood	Shaly limestone	12.93 - 26.06	2.68	_	_	_	_	
		Trenton	Limestone	35.41	2.68 *v*	_	_	_	_	
				35.53	2.68 *h*	_	_	_	_	
				35.48	2.85 *i*	_	_	_	_	
		Rochester	Shale	26.37	2.77 *v*	_	_	_	38.7 *v*	
				26.24 - 26.5	2.68 - 2.72 *h*	_	_	_	39.4 *h*	
				26.29	2.74 *i*	_	_	_	21.8 *i*	
		Lockport (Goat Island)	Dolomite	169.37	2.76	_	_	_	61.9 *v*	
				168.8	2.76	_	_	_	70.3 - 80.2 *h*	
				169.21	2.77	_	_	_	74.5 *i*	
		Lockport (Gasport)	Dolomitic limestone	165.66	2.72 *v*	_	_	_	73.8 *v*	
Southern Ontario	Research Program For The National Research Council of Canada, Different Sites in Southern Ontario	Lockport (Gasport)	Dolomitic limestone	165.57	2.76 *h*	_	_	_	70.3 - 86.5 *h*	[5]
				165.74	2.72 *i*	_	_	_	69.6 *i*	
		Lockport (Gasport)	Dolomitic limestone/ Limestone	164.06	2.72 *v*	_	_	_	47.8 *v*	
				164.17	2.71 - 2.72 *h*	_	_	_	53.4 - 66.1 *h*	
				164..01	2.76 *i*	_	_	_	60.5 *i*	
Ontario/ Toronto	Darlington intake tunnel	Whitby	Shaly limestone	83.4	2.58 - 2.70	5.1 - 5.12 *v*	1.01 - 2.49	0.34 - 0.37 *v*	39.6 - 43.6 *v*	[4] [25]
				84.4 - 84.7	_	4.92 - 5.13 *h*	_	0.25 - 0.27 *h*	52.9 - 54.6 *h*	
Ontario /Niagara Falls	Sir Adam Beck Niagara generating station (SABNGS) No. 3	Queenston	Shale	95.64 - 114.33	2.66 - 2.68	3.48 - 4.28	_	_	_	[6]

v: results from vertically cored samples/or measurements in the vertical direction; *h*: results from horizontally cored samples/or measurements in the horizontal direction; *i*: results from inclined 45˚ cored samples with respect to the bedding planes.