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IN SITU DETERMINATION OF DYNAMIC ELASTIC MODULI OF ROCK.

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A simple economic method has been developed for determining the in situ compressional and shear velocities in rock from which its elastic constants can be calculated. Measurements were made by the Bison Seismograph in an underground magnesite opening of Jelsava. By hammer blows, both compressional and shear waves were generated. Velocity gages mounted to the rock surface were used to record the arrival time for both waves over travel path. The theory of elasticity shows that all dynamic elastic moduli for a material can be calculated from knowledge of density plus compressional and shear velocities. Measurement procedures for density and compressional waves are reasonably standard and well known. Procedures for obtaining shear velocities are less straightforward. We limit our consideration in this paper to in situ measurements of shear velocities. From the arrival time measurements, the compressional and shear velocities were calculated. From these velocities and density of rock, the elastic constants were calculated. Young s modulus and Poisson s ratio provide the essential rock property data for studying deformation of mine openings and mine structures or rock outcrops, since their permit calculating the principal stresses from strain-strain measurements. The ever-growing field of rock mechanics demands a new effort in determining the elastic constants of rock. This technique could be relatively simple and economical to apply in underground mine openings or at rock outcrops.

INTRODUCTION

Based on the principals of physics, the velocity of seismic waves depends on dynamic elastic constants of rock /1/. The theory of elasticity shows, when shear-propagation velocity, compressional - propagation velocity, and density are known, all elastic moduli for a material can be calculated.
The determination of compressional - propagation in rock is routine field measurement. A small impact on a surface is evoked and the arrival time of primary wave at a geophone at a known distance from the sot point is recorded. Density is determined through standard laboratory tests. A survey of methods for determining shear waves did not reveal any simple techniques.

Most procedures require large, unwieldy mechanism, such as air cannons or large, bulky pendulums suspended in A frames to develop a unidirectional force for generating shear waves. Seismic sources for shear waves are often designed to generate either dominantly P and SV or dominantly SH. The reason lies in fundamentally different behaviour of SV and SH wave at boundary. In practice, the distinctiveness of SH waves is enhanced because most seismic sources designed to produce SV waves will also produce substantial P waves. Than seismic waveform may include a complicated sequence of arrivals consisting of direct and converted P and SV waves. By contrast, careful design of an SH-type seismic source should minimize arrival of other wave types. Seismic detectors placed on or near ground surface may record motion which differs markedly in direction, amplitude, and phase from the incited wave motion. The effect on incident P and SV waves can be quite complicated unless the direction of wave arrival is close to vertical. In the later case, an incident P wave will appear principally on a radial - horizontal detector. For all other angles of incidence, however, either type of incident wave will produce both vertical and horizontal components of motion.

Seismic shear waves present a large and varied subject matter. We confine our attention here to use of shear waves for determining dynamic elastic moduli. Various elastic constants of rock are needed for calculating the deformation effects on rock.

EXPERIMENTAL PROCEDURE

In application of rock mechanics is conducted in situ by seismic methods. The are based on measuring the velocities at which artificially excited elastic waves are spreading through the rocks. Measurements were made by the Bison Seismograph /2/.

Tests were conducted in the Magnesite Outcrop of Jelsava. The plan of test area is shown in fig. 1. There are three parts at the opening, marked P1, P2, and P3. As shown in this plan a number of impact sources were used in each part; in part P1 there is one impact point marked I1 and there are 6 geophones marked G1, G2, G3, G4, G5, and G6; in part P2 there are four impact points -I1,...,I4 and four geophones - G1,...,G4; in part P3 there are two impact points -I1, I2, and six geophones G1,...,G6. About 1/3 of part P1 is exploited and marked with comas.

In preparing the test sites a series of shallow holes were drilled from a free surface. The holes, all of which were 1-1.5 cm in diameter and about 10 cm deep, were drilled horizontally into rock. There were used for both geophones and impacts. Vertically drilled holes on the bottom of the pillars were only used as impact points. They were about 10 cm - long simple steel studs mounted in the rock holes drilled in both the floor and wall of the drift.

Detectors were mounted onto the protruding ends of 10 - cm steel beams grouted into geophone holes in the wall. Geophone mounts consisting of steel members bolted to 5 cm -

long studs were mounted in the protruding ends. The geophones were attached and oriented to measure particle motion. The standard moving - coil seismic geophone has been used. Both vertical and horizontal units were available. These detectors translated earth motions into electrical signals, which were carried by cables to seismograph Bison where it is amplified and displayed as a true seismic waveform of the waves s travel time. The capability of this engineering seismograph has been dramatically increased by the use Bison Signal Enhancement concept by which seismic waves from impact sources are stored and summed.

In an attempt to solve the problem of the shear waves, several steps were taken to provide unambiguous identification of the shear wave arrival on the seismic waveform. This rely on the distinctive features of shear wave propagation.

The first step is to use a source which produces the largest possible shear waves and the smallest part waves of other types. A seismic source will generate shear waves to the extent that it is directional, unbalanced, and asymmetric; nearly all practical seismic sources posses these properties to a greater or lesser extent. The trust of shear wave source design has therefore taken the direction of suppressing other unwanted wave types. Most workers have attempt to generate a horizontal force and to make measurements along a line perpendicular to it. To the extent that source symmetry can be achieved, P, SV, and Raleigh waves will be suppressed, leaving only SH, and possibly Love waves.

The second step is to make measurements at a location where the source radiation pattern predicts the largest shear wave amplitudes with respect to the other types. for a horizontal surface force, measurements along a perpendicular line would detect principally SH waves.

The third step is to oriented the detector to take maximum advantage of the directionality of the shear waves.

Transverse detectors which respond to the motion perpendicular to the line joining source and detector would be used.

In respect to this we arranged some specific field procedures in undermine pillars (fig.1). We used horizontal force with transverse - horizontal detectors. This arrangement should produce and detect purely SH waves. Identification of SH waves can be greatly strengthened by a simple modification of the field procedure. An impact first in one direction and than in the opposite direction at the source position should produce two signals and thereby enhance SH with' respect to the other wave types. Substraction can be accomplished either by reversing the geophone input connection or by rotating the geophone 180 between impacts.

After identification of SH waves, the problem remains of computing the shear velocities. If path can be verified, then V_s=path/T, where T is arrival time at detector. A complicating factors arises when the propagation path so es not follow a straight line from source receiver. This may occur whenever materials with different shear velocities are presented. The he seismic wave follows a minimum - time path rather than a minimum - distance path. This may produce a refracted or reflected waves whose actual path diverges markedly from straight line.

We made three in situ measurements at different time - on March 1st, 1990; on November 28th, 1990 after exploiting about 2/3 of the rockmass in one measuring part (marked with commas); and on January 25th, 1991 after total exploitation of this part so as to judge the deformation state of magnesite pillars during the process of exploitation.

DATA AND ANALYSIS

Tables 1, 2, 3 and 3 give all the pertinent data concerning detectors, arrival times, and distance for the test. In analyzing the field data, all constants have been calculated from obtained velocities and the magnesite density through the following equations /3/

$$\text{Poisson s ratio}\quad \sigma=\frac{(\frac{V_p}{V_s})^2-2}{2(\frac{V_p}{V_s})^2-2} \qquad (1)$$

$$\text{Youngs modulus}\ E=\frac{\varrho V_s^2[3(\frac{V_p}{V_s})^2-4]}{(\frac{V_p}{V_s})^2-1} \qquad (2)$$

$$\text{Modulus of rigidity}\ G=\varrho V_s^2 \qquad (3)$$

$$\text{Lame s constant}\quad \lambda=\varrho V_s^2[(\frac{V_p}{V_s})^2-2] \qquad (4)$$

$$\text{Bulk modulus}\quad k=\varrho V_s^2[(\frac{V_p}{V_s})^2-\frac{4}{3}] \qquad (5)$$

where ρ is density,
v_p is compressional velocity
v_s is shear velocity.

As a rule of thumb, Poisson s ratio had been calculated to evaluate the reliability of the other elastic constants. We have used the density of magnesite as 5.10^3 $kg.m^{-3}$ /4/.

A comparison of these results shows that some significant dependencies exist. the velocities of seismic waves increase with time. This increase is probably due to the additional stress caused by exploitation. Results reached testifies that the rock is probably not disturbed;

undisturbed parts of rock are characterised by high velocities. the same can be seen from values of dynamic elastic moduli.

From this studies in implies that this method is sufficient sensitive to ascertain the state of strain o magnesite pillars during the process of exploitation. The forecast a destruction of the mine opening it is necessary to continue at measuring in large extent.

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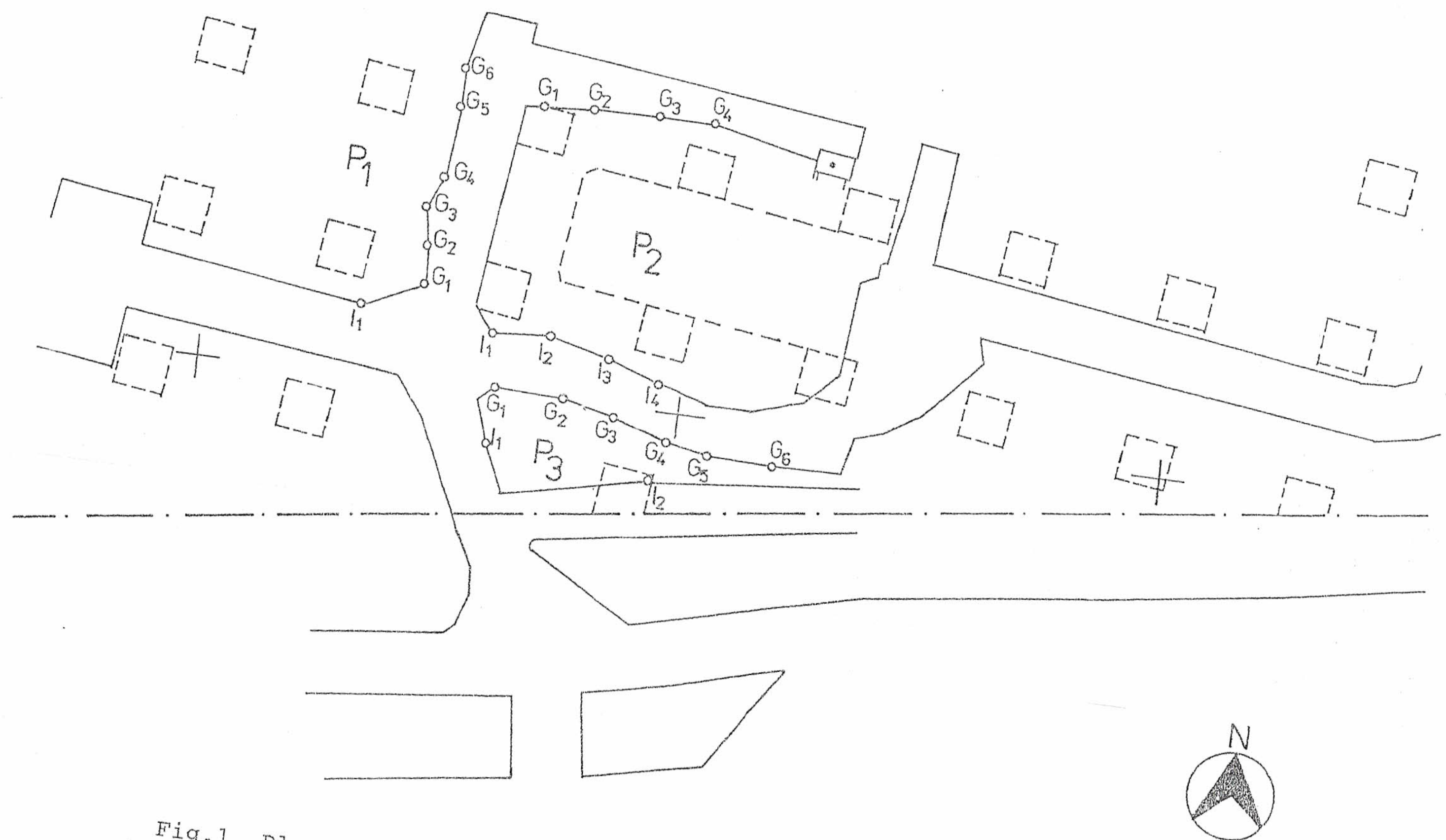

Fig.1 Plan of test area for velocity study in mine opening Jelsava

TABLE 1. VELOCITY AND CONSTANTS ARRAY DATA FOR TEST CONDUCTED IN PART P1

Date	IMPACT	RESPONSES	DISTANCE metres	TIME OF ARRIVAL P wave, $x10^{-3}$ seconds	TIME OF ARRIVAL S wave, $x10^{-3}$ seconds	VELOCITY OF P wave [m/s]	VELOCITY OF S wave [m/s]	POISSON'S RATIO	E $x10^{11}$ [N.m^{-2}]	G $x10^{10}$ [N.m^{-2}]	$x10^{11}$ [N.m^{-2}]	k $x10^{11}$ [N.m^{-2}]
MARCH 1st, 1990	I1	61	6.76	1.00	1.98	6762	3415	.329	1.55	5.83	1.12	1.51
		62	8.69	1.30	2.58	6834	3444	.330	1.58	5.93	1.14	1.54
		63	11.48	1.66	3.30	6915	3478	.331	1.61	6.05	1.18	1.58
		64	14.85	2.20	4.40	6740	3374	.333	1.52	5.69	1.14	1.52
		65	21.51	3.98	7.90	5407	2723	.330	0.98	3.71	0.72	0.97
		66	25.96	5.34	10.60	4862	2449	.330	0.80	3.00	0.58	0.78
NOV. 28th, 1990	I1	61	6.76	0.92	1.82	7315	3750	.320	1.83	6.90	1.32	1.78
		62	8.87	1.20	2.38	7404	3733	.330	1.85	6.98	1.35	1.81
		63	11.48	1.54	3.06	7453	3751	.330	1.87	7.03	1.37	1.84
		64	14.85	2.00	3.96	7423	3730	.331	1.85	6.96	1.36	1.83
		65	21.51	3.20	6.36	6723	3371	.332	1.51	5.68	1.12	1.50
		66	25.96	3.92	7.80	6623	3329	.331	1.48	5.54	1.08	1.45
JAN. 25th, 1991	I1	61	6.76	0.84	1.68	8050	4025	.333	2.16	8.10	1.62	2.15
		62	8.69	1.12	2.22	7933	4002	.329	2.13	8.01	1.54	2.08
		63	11.48	1.44	2.86	7471	4014	.330	2.14	8.06	1.57	2.10
		64	14.85	1.86	3.70	7982	4012	.331	2.14	8.05	1.58	2.11
		65	21.51	2.80	5.56	7682	3869	.330	1.99	7.48	1.45	1.95
		66	25.96	3.84	7.64	6761	3398	.331	1.54	5.77	1.30	1.51

TABLE 2. VELOCITY AND CONSTANTS ARRAY DATA FOR TEST CONDUCTED IN PART P2

DATE	IMPACT	GEOPHONES	DISTANCE metres	TIME OF ARRIVAL P wave, $x10^{-3}$ seconds	TIME OF ARRIVAL S wave, $x10^{-3}$ seconds	VELOCITY OF P wave [m/s]	VELOCITY OF S wave [m/s]	POISSON'S RATIO	E $x10^{11}$ [N.m^{-2}]	G $x10^{10}$ [N.m^{-2}]	$x10^{11}$ [N.m^{-2}]	k $x10^{11}$ [N.m^{-2}]
MARCH 1st, 1990	I1	G1	23.33	3.08	6.00	7593	3980	.322	2.00	7.56	1.37	1.87
		G2	25.07	3.30	6.42	7596	3904	.321	2.01	7.62	1.36	1.87
		G3	27.77	3.66	7.14	7587	3889	.322	2.00	7.56	1.37	1.87
		G4	31.15	4.10	8.00	7598	3894	.322	2.00	7.58	1.37	1.88
	I2	G1	23.39	3.16	6.15	7402	3803	.321	1.91	7.23	1.29	1.78
		G2	23.81	3.12	6.10	7630	3902	.323	2.01	7.61	1.38	1.89
		G3	25.10	3.34	6.50	7514	3861	.321	1.95	7.45	1.33	1.83
		G4	27.52	3.64	7.10	7560	3876	.322	1.98	7.51	1.35	1.85
	I3	G1	25.92	3.38	6.58	7668	3938	.321	2.04	7.75	1.38	1.90
		G2	25.16	3.32	6.46	7579	3895	.321	2.00	7.58	1.35	1.86
		G3	24.96	3.30	6.42	7563	3887	.320	2.00	7.55	1.35	1.85
		G4	26.14	3.38	6.58	7735	3973	.321	2.08	7.89	1.41	1.94
	I4	G1	30.31	4.00	7.80	7579	3886	.322	2.00	7.55	1.35	1.86
		G2	28.70	3.78	7.36	7593	3900	.321	2.01	7.60	1.36	1.87
		G3	27.21	3.60	7.02	7560	3877	.322	1.99	7.52	1.35	1.85
		G4	27.10	3.38	6.60	8067	4107	.325	2.23	8.43	1.57	2.12
NOV. 26th. 1990	I1	G1	23.33	2.68	5.22	8704	4469	.321	2.63	9.98	1.76	2.46
		G2	25.07	2.85	5.57	8764	4500	.321	2.67	10.12	1.82	2.49
		G3	27.80	3.68	7.70	-	-	-	-	-	-	-
		G4	31.15	4.40	8.74	-	-	-	-	-	-	-
	I2	G1	23.39	2.70	5.26	8662	4447	.321	2.61	9.87	1.77	2.43
		G2	23.81	2.68	5.22	8882	4560	.321	2.74	10.39	1.86	2.55
		G3	25.10	3.95	7.86	-	-	-	-	-	-	-
		G4	27.52	4.36	8.60	-	-	-	-	-	-	-
	The	next	place	has been	exploited	-	-	-	-	-	-	-

TABLE 3. VELOCITY AND CONSTANTS ARRAY DATA FOR TEST CONDUCTED IN PART P3

Date	IMPACT	GEOPHONES	DISTANCE metres	TIME OF ARRIVAL P wave, $x10^{-3}$ seconds	TIME OF ARRIVAL S wave, $x10^{-3}$ seconds	VELOCITY OF P wave [m/s]	VELOCITY OF S wave [m/s]	POISSON'S RATIO	E $x10^{11}$ [N.m^{-2}]	G $x10^{10}$ [N.m^{-2}]	$x10^{11}$ [N.m^{-2}]	k $x10^{11}$ [N.m^{-2}]
MARCH 1st, 1990	I1	G1	6.56	0.92	1.76	7125	3724	.312	1.82	6.93	1.15	1.61
		G2	9.49	1.32	2.54	7181	3731	.315	1.83	6.96	1.18	1.65
		G3	15.62	2.14	4.12	7299	3792	.315	1.89	7.19	1.22	1.71
		G4	18.55	2.56	4.92	7246	3770	.314	1.86	7.11	1.20	1.68
		G5	23.14	3.28	6.30	7054	3672	.314	1.77	6.74	1.14	1.59
		G6	29.57	4.08	7.84	7247	3771	.314	1.87	7.12	1.20	1.67
	I2	G1	17.97	2.50	4.80	7189	3744	.314	1.84	7.01	1.18	1.64
		G2	12.69	1.76	3.38	7209	3753	.314	1.85	7.04	1.19	1.65
		G3	11.75	1.64	3.16	7163	3718	.315	1.82	6.91	1.18	1.64
		G4	4.72	0.64	1.22	7381	3872	.310	1.96	7.49	1.22	1.72
		G5	7.25	1.00	1.92	7246	3774	.314	1.87	7.12	1.20	1.68
		G6	12.95	1.78	3.42	7277	3787	.314	1.88	7.17	1.21	1.69
NOV. 28th, 1990	I1	G1	6.56	0.76	1.46	8618	4490	.314	2.65	10.08	1.70	2.37
		G2	9.48	1.10	2.12	8617	4471	.316	2.63	9.94	1.71	2.39
		G3	15.62	1.80	3.45	8678	4514	.314	2.69	10.19	1.73	2.41
		G4	18.55	2.12	4.08	8749	4546	.315	2.72	10.33	1.76	2.45
		G5	23.14	2.68	5.16	8633	4484	.315	2.64	10.05	1.72	2.39
		G6	29.57	3.40	6.54	8696	4521	.315	2.68	10.22	1.74	2.42
	I2	G1	17.97	2.08	4.00	8640	4493	.315	2.65	10.08	1.71	2.39
		G2	12.69	1.46	2.80	8699	4531	.313	2.70	10.26	1.72	2.41
		G3	11.75	1.34	2.60	8767	4510	.319	2.69	10.21	1.80	2.40
		G4	4.72	0.54	1.04	8748	4542	.315	2.71	10.31	1.76	2.45
		G5	7.25	0.84	1.62	8626	4473	.316	2.63	10.00	1.71	2.38
		G6	12.95	1.50	2.88	8635	4490	.314	2.66	10.11	1.70	2.38
JAN. 25th, 1991	I1	G1	6.56	0.70	1.34	9364	4892	.312	3.14	11.97	1.99	2.79
		G2	9.48	1.02	1.96	9293	4836	.314	3.07	11.69	1.98	2.76
		G3	15.62	1.66	3.20	9410	4881	.316	3.14	11.91	2.04	2.84
		G4	18.55	1.98	3.80	9369	4881	.314	3.13	11.91	2.01	2.80
		G5	23.14	2.50	4.80	9255	4820	.314	3.05	11.61	1.96	2.73
		G6	29.57	3.22	6.23	9183	4759	.315	2.94	11.37	1.94	2.70
	I2	G1	17.97	1.96	3.80	9077	4723	.314	2.94	11.18	1.88	2.63
		G2	12.69	1.38	2.65	9192	4789	.309	2.99	11.37	1.95	2.71
		G3	11.75	1.28	2.46	9178	4776	.314	3.00	11.41	1.93	2.69
		G4	4.72	0.50	0.96	9440	4921	.314	3.18	12.11	2.04	2.84
		G5	7.25	0.78	1.50	9290	4831	.315	3.07	11.67	1.98	2.76
		G6	12.95	1.42	2.74	9121	4727	.316	2.94	11.17	1.92	2.67