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Application of Sound Level for Estimating Rock Properties

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1. Introduction

The process of drilling, in general, always produces sound as a by-product. This sound is generated from the rock-bit interface, regardless of the material the bit is drilling in. The drillability of rock depends on many factors, like bit type and diameter, rotational speed, thrust, flushing and penetration rate. Sound is used as a diagnostic tool for identification of faulty components in the mechanical industry. However, its application in mining industry for estimating rock properties is not much explored. Knowledge of rock properties is essential for mine planning and design. The rock properties such as compressive strength, porosity, density etc. are uncontrollable parameters during the drilling process. The rock properties must be determined at a mine or construction site by testing a sample. There are various techniques for the determination of rock properties in the laboratory and the field. International Society of Rock Mechanics (ISRM) and American Society for Testing and Materials have suggested or standardised the procedure for measuring the rock strength. However, the method is time consuming and expensive. As an alternative, engineers use empirical and theoretical correlations among various physico-mechanical properties of rock to estimate the required engineering properties of rocks.

Most of the works in the application of sound levels are in other branches of engineering (Vardhan et al., 2004, 2005, 2006; Vardhan & Adhikari, 2006). A couple of studies in oil and gas industries have proposed a technique called "Seismic–While–Drilling" for estimating rock formations. For instance, few studies have proposed the use of noise produced by the bit during drilling as a seismic source for surveying the area around a well and also for formation characterization while drilling (Onyia, 1988; Martinez, 1991; Rector & Hardage, 1992; Miranda, 1996; Asanuma & Niitsuma, 1996; Hsu, 1997; Aleotti et al., 1999; Tsuru & Kozawa, 1998; Hand et al., 1999; Fernandez & Pixton, 2005). A recent study (Stuart et al., 2004) has also reported a method of estimating formation properties by analyzing acoustic waves that are emitted from and received by a bottom hole assembly. It needs to be emphasized that "Seismic–While–Drilling" technique is different from the technique of estimating rock properties using sound levels produced during drilling.

For rock engineering purpose, very limited publications are available on this subject. The usefulness of sound level in determining rock or rock mass properties has been shown clearly only in two publications (Roy & Adhikari, 2007; Vardhan & Murthy, 2007) and the need for further work in this area has been suggested. It is anticipated that the sound level with drilling in rocks of different physico-mechanical properties will be different for the same type of drill machine. Keeping this point in mind, the present research work was undertaken.

This chapter reveals some investigations (both laboratory and field) carried out to estimate the rock properties using sound levels produced during drilling.

2. Laboratory investigations

The noise measurement for the same type of drill machine varies from strata to strata. Thus, the variations in the sound level can indicate the type of rock, which can be used to select suitable explosives and blast designs. Rock characterization while drilling is not a new idea. Devices for monitoring the drilling parameters such as thrust, drilling depth and penetration are available and the information obtained are used for blast designs. However, the concept of rock characterization using sound levels is new. Therefore, laboratory investigations were caried out using small portable pneumatic drilling equipment and Computer Numerical Controlled (CNC) machine with carbide drill bit set–up along with noise measuring equipments.

2.1 Laboratory investigations using portable pneumatic drilling equipment

2.1.1 Experimental setup

In the laboratory, all the sound level measurements were conducted on pneumatic drill machine operated by compressed air. The experimental set–up was in a normal cement plastered room of 5 m width, 9 m length and 5 m height. The important specifications of the pneumatic drill used were:

- Weight of the pneumatic drill machine (28 kg)
- Number of blows per minute - 2200
- Type of drill rod - Integrated drill rod with tungsten carbide drill bit
- Recommended optimum air pressure - 589.96 kPa

A lubricator of capacity 0.5 litres and a pressure gauge with a least count of 49 kPa were provided between the compressor and pneumatic drill machine to lubricate the various components and to regulate the air pressure supplied to the drill machine, respectively. A percussive drill setup to drill vertical holes was fabricated to carry out the drilling experiments for sound level measurement on a laboratory scale (Fig. 1). The base plate of the setup consists of two 12.5 mm thick I-sections (flange width - 1 cm and height – 30 cm) which are welded together all along the centre. They are firmly grouted to the concrete floor with the help of four 3.8 cm diameter anchored bolts. Two circular guiding columns of 60 mm diameter, 175 cm long, and 55 cm apart were secured firmly to the base plate. The verticality of the two columns was maintained with the help of a top plate (3.8 cm thick, 13 cm width and 62.5 cm length). On the top of the base plate, 25.4 mm diameter holes were drilled at close intervals on two opposite sides for accommodating different sizes of rock blocks (up to 500 mm cube). The rock block was firmly held on the base plate with the help of two mild steel plates (1 cm thick, 7.5 cm width and 61 cm length) kept on the top of the rock block and four 25.4 mm bolts, placed at the four corners.

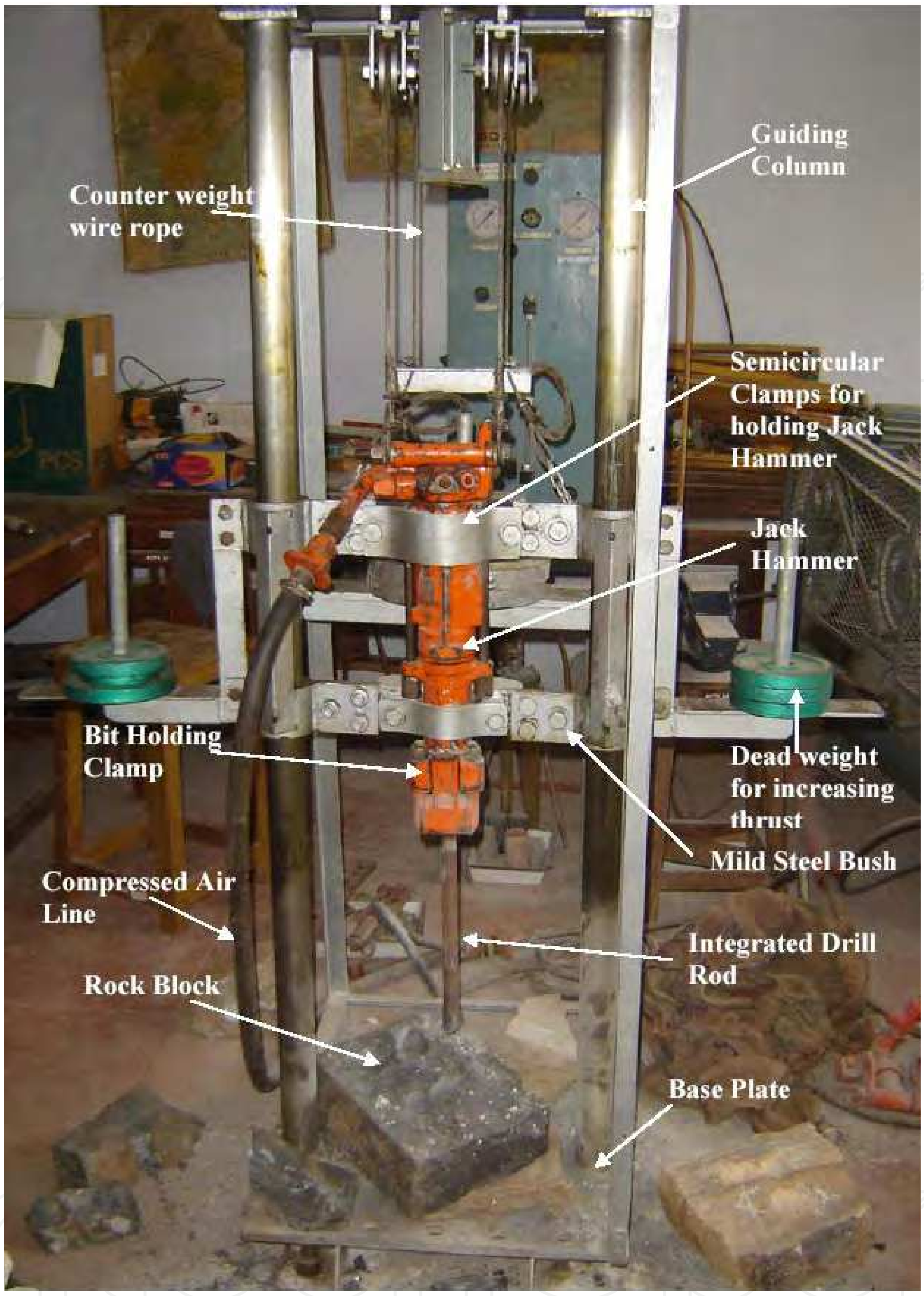

Fig. 1. Pneumatic drill setup for drilling vertical holes in rock blocks

The pneumatic drill was firmly clamped at its top and bottom with the help of four semicircular mild steel clamps, which were in turn bolted firmly to four mild steel bushes for frictionless vertical movement of the unit over the two guiding columns of the setup. In order that the top and bottom clamps work as one unit, they were firmly connected with the help of four vertical mild steel strips (1.3 cm thick, 5 cm width and 50 cm length) on each side of the pneumatic drill. For increasing the vertical thrust, two vertical mild steel strips (1.3 cm thick, 5 cm width and 32 cm length) were bolted to the top and bottom clamps. On this strip, dead weights made up of mild steel were fixed with the help of nut and bolt arrangements. For conducting drilling experiments at low thrust level (less than the dead weight of the drill machine assembly), a counter weight assembly was fabricated. For this purpose a steel wire rope (0.65 cm diameter) was clamped to the top of the pneumatic drill unit which in turn passed through the pulley arrangements located at the top plate of the setup. A rigid frame was firmly grouted to the shop floor at a distance of 86 cm from the experimental setup. The steel wire rope from the experimental setup was made to pass over the pulley mounted on the rigid frame. At the other end of the rope, a plate was fixed for holding the counter weights. The dead weight of pneumatic drill machine and accessories for vertical drilling was 637 N. With the help of counter–weight arrangement, it was possible to achieve a desired thrust value as low as 100 N. Similarly, through the arrangement of increasing the thrust level, it was possible to achieve a thrust value as high as 900 N.

2.1.2 Rock samples used in the investigation

Sound level measurement on pneumatic drill set up was carried out for five different rock samples obtained from the field. These rock samples were gabbros, granite, limestone, hematite and shale. The size of the rock blocks was approximately 30 cm x 20 cm x 20 cm.

2.1.3 Instrumentation for noise measurement

Sound pressure levels were measured with a Larson-Davis model 814 integrating averaging sound level meter. The instrument was equipped with a Larson Davis model 2540 condenser microphone mounted on a model PRM904 preamplifier. The microphone and preamplifier assembly were mounted directly on the sound level meter. The acoustical sensitivity of the sound level meter is checked once a year. For all measurements, the sound level meter was handheld. To determine the noise spectrum, the instrument was set to measure A–weighted, time-averaged one-third-octave-band sound pressure levels with nominal midband frequencies from 25 Hz to 20 kHz. The sound level meter was also set to measure A–weighted equivalent continuous sound levels (Leq). For each measurement, the sound level meter was set for an averaging time of 2 minutes.

2.1.4 Determining the compressive strength and abrasivity of rock specimens

The compressive strength of rock samples was determined indirectly using Protodyakonov’s apparatus. Protodyakonov index for estimation of compressive strength of rock samples is an indirect and time-consuming method. However, this method was chosen due to limited availability of any particular type of rock samples in the laboratory. Therefore, first sound level measurement using drilling was carried out. Then the same drilled rock block was used for determining compressive strength and abrasivity. It was difficult to prepare samples for determining uniaxial compressive strength from these drilled rock blocks.

Abrasion test measures the ability of rocks to wear the drill bit. This test includes wear when subject to an abrasive material, wear in contact with metal and wear produced by contact between the rocks. For this purpose, Los Angele’s abrasion test apparatus was used.

The results of the experimental study for the compressive strength and the abrasivity of the rock samples are given in Table 1. It is seen that, with increase in compressive strength of rock samples, the abrasivity decreases. This is due to increase in the resistance of rocks to wear with increase in the compressive strength.

Block No.	Rock Type	Compressive strength (kg/cm²)	Abrasivity (%)
Block 1	Shale	1051.35	23.70
Block 2	Hematite	1262.33	21.50
Block 3	Limestone	1542.57	20.30
Block 4	Granite	1937.13	17.50
Block 5	Gabros	2252.35	15.50

Table 1. Compressive strength and abrasivity of different rocks

2.1.5 Noise measurement

A set of four test conditions was defined for measurement of sound spectra which is given in Table 2. The measurement of sound spectra was carried out on pink granite. For the test conditions A2, A3 and A4 mentioned in Table 2, the air pressure was constant at 6 kg/cm². For test condition A1, the sound spectrum was measured at the operator's position and without actually operating the drill machine. This background noise was mainly due to the compressor operating near the pneumatic drill setup. Test condition A2 in the table refers to the measurement of sound spectra at the operator's position by opening the exhaust of the drill but without carrying out any drilling operation. Test conditions A3 and A4 refer to measurement of noise spectra during drilling at the operator's position with 100 N and 300 N thrust respectively.

Noise sources measured at operator position	Test condition
Background	A1
Air only	A2
Air + drill with 100 N thrust	A3
Air + drill with 300 N thrust	A4

Table 2. Test conditions for determination of sound spectra

For measuring the variation in sound level while drilling in rocks of different compressive strength and abrasivity, the rock blocks were kept beneath the integrated drill rod of the pneumatic drill. Sound level measurements were carried out for thrust values of 160, 200, 300 and 360 N on each rock block. It is worth mentioning here that the realistic thrust values used by drill operators in the field vary based on the type of rock encountered at a particular site. Typical thrust values in the field may vary from 150 to beyond 500 N. For each thrust mentioned above, the A–weighted equivalent continuous sound level (L_{eq}) was measured by holding the sound level meter at 15 cm distance from the drill bit, drill rod and the exhaust for air pressure values of 5.0, 5.5, 6.0 and 7.0 kg/cm². Similarly, the L_{eq} level was measured at the operator's position for each thrust of 160 to 360 N and air pressures of 5 to 7 kg/cm² as mentioned above. The operator's position refers to the position of the operator's ear which was at a height of 1.7 m from the ground level and 0.75 m from the center of the experimental set-up. During measurement, all the doors and windows of the room were kept open so as to reduce the effect of reflected sound.

For a particular condition, at each microphone location and for the same rock block, the sound level was determined five times in relatively rapid succession. The arithmetic average of the A-weighted sound pressure levels from each set of five measurements was computed to yield an average A-weighted sound level for a particular condition.

2.1.6 Noise assessment of pneumatic drill under various test conditions at operator's position

The noise spectrum at the operator's position for test conditions A1 and A2 are shown in Fig. 2. It is seen that the background sound level at the measurement location due to the operation of the air compressor alone is below 82 dB with the nominal one-third-octave midband frequencies from 25 Hz to 20 kHz. Also, the increase in sound level with midband frequencies above 50 Hz is more than 10 dB for test condition A2 relative to that of test condition A1. Therefore, the sound level in the frequency range of 63 Hz to 20 kHz for test condition A2 is unlikely to be affected by the background noise due to the compressor. However, the sound level for test condition A2 may be affected due to test condition A1 with nominal midband frequencies from 25 to 50 Hz as the difference in sound level in this range of frequency is below 9 dB.

The noise spectrum at the operator's position for test conditions A2, A3 and A4 are shown in Fig. 3. It is seen that from 50 to 100 Hz, the increase in sound level for test condition A3 relative to that of A2 is from 2.8 to 7.2 dB and that of A4 relative to that of A3 is from 3.2 to 5.9 dB. This shows that drilling operation has increased the sound level with midband frequencies from 50 to 100 Hz. The increase in sound level in this frequency range (50 – 100 Hz) is due to impact between the piston and the drill steel and that between the drill steel and the rock. The increase in sound level for test condition A3 relative to that of A2 with midband frequencies from 125 Hz to 2 kHz is in the range of 1.0 to 11.7 dB and that of A4 relative to that of A3 is in the range of 1.6 to 6.0 dB. The noise in this frequency range (125 Hz – 2 kHz) is due to the exhaust of the drill machine. The combination of drilling noise and exhaust noise has resulted in increase of sound level in this frequency range (125 Hz – 2 kHz). There is significant increase in sound level of the order of 6.6 to 14.2 dB from 2.5 to 20 kHz for test condition A3 relative to that of A2 and 4.0 to 7.7 dB for test condition A4 relative to that of A3. This increase in sound level is due to resonance of the steel parts of the drill steel due to rock drilling.

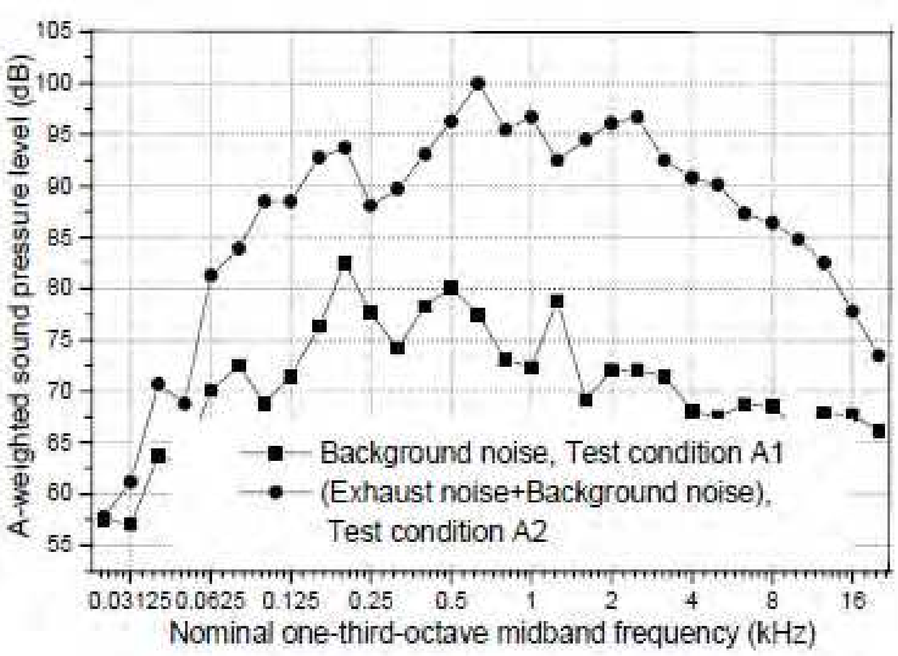

Fig. 2. Effect on L_{eq} levels at the operator's position for test conditions A1 and A2

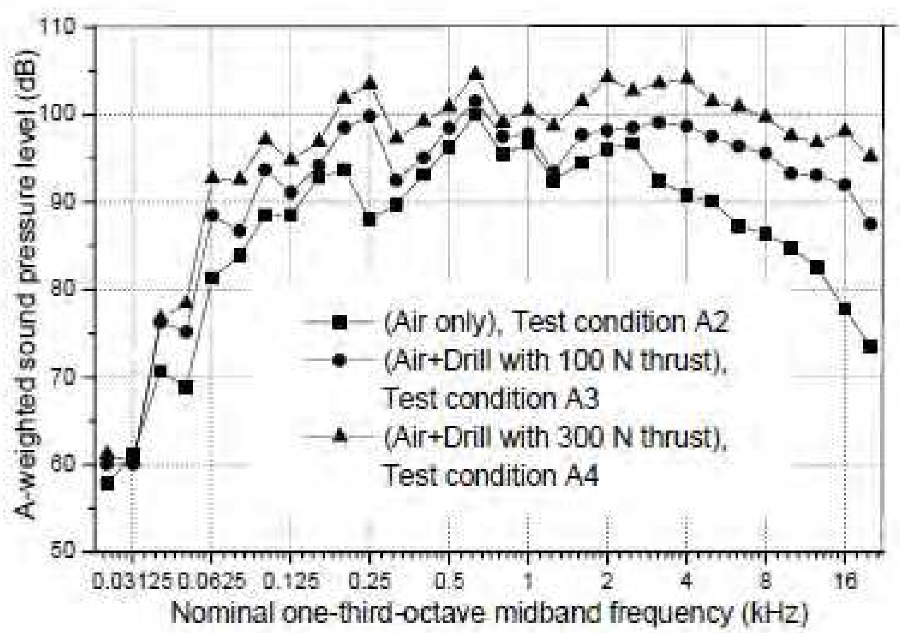

Fig. 3. Effect on L_{eq} levels at the operator's position for test conditions A2, A3 and A4

2.1.7 Effect of rock properties on sound level of pneumatic drill

a. At operators position

The L_{eq} level at the operator's position for different rocks of varying strength at various thrusts and air pressures are given in Table 3. In this table, the compressive strengths of rocks are given in increasing order i.e., shale has the lowest compressive strength and the highest abrasivity whereas gabro has the highest compressive strength and the lowest abrasivity. At an air pressure of 5 kg/cm^2 and thrust of 160 N, the difference in A–weighted sound level for different rocks was of the order of 0.8 dB, which varied from 0.8 to 1.4 dB with an increase in the thrust from 160 to 360 N. At an air pressure of 5.5 kg/cm^2, and a thrust of 160 N, the difference in A-weighted sound level for different rocks was 0.9 dB. At this air pressure (5.5 kg/cm^2), an increase in the thrust from 160 to 360 N caused an increase in the sound level by 1.6 dB. Similar results were observed at air pressures of 6 and 7 kg/cm^2 with an increase in the thrust from 160 to 360 N.

The effect of air pressure on sound levels at constant thrust of 160 N for different rock samples at operator's position is shown in Fig. 4. An increase in sound level is observed with increasing air pressure values. With an increase in air pressure by 2 kg/cm^2, i.e., from 5 to 7 kg/cm^2 and at a thrust of 160 N, the sound level of block-1 increased by 1.6 dB. Similar results were shown by other rock samples too. The increase in sound level for different rocks (Block-1 to Block-5) with an increase in the air pressure by 2 kg/cm^2 at a thrust of 160 N is 1.9, 2.1, 2.2 and 2.4 dB respectively.

The effect of compressive strength of rock on sound level at operator's position for a constant thrust of 160 N and for different air pressure values is shown in Fig. 5 The above result shows that an increase in the compressive strength and a decrease in the abrasivity of rocks increase the sound level. It is worth mentioning that, to maintain optimum penetration rate, the thrust and air pressure must be increased in rocks having higher compressive strength and lower abrasivity, which in turn results in higher sound levels.

Air pressure (kg/cm²)	Thrust (N)	Shale	Hematite	Limestone	Granite	Gabros
5	160	116.7	116.9	117.0	117.3	117.5
	200	116.9	117.3	117.3	117.5	117.8
	300	117.8	117.9	118.1	118.3	118.7
	360	118.2	118.3	118.5	118.8	119.6
5.5	160	116.9	117.1	117.2	117.4	117.8
	200	117.3	117.5	117.7	117.9	118.2
	300	118.3	118.9	119.1	119.5	119.7
	360	118.7	119.5	119.8	119.9	120.3
6	160	117.9	118.1	118.6	118.9	119.2
	200	118.4	118.5	118.9	119.3	119.5
	300	119.2	119.8	120.1	120.5	120.7
	360	119.8	120.2	120.5	120.8	121.3
7	160	118.3	118.8	119.1	119.5	119.9
	200	118.6	119.2	119.5	119.7	120.3
	300	119.5	120.3	120.7	121.1	121.7
	360	120.2	120.8	121.1	121.9	122.2

Table 3. L_{eq} level at the operator's position for different rocks at various thrust and air pressures

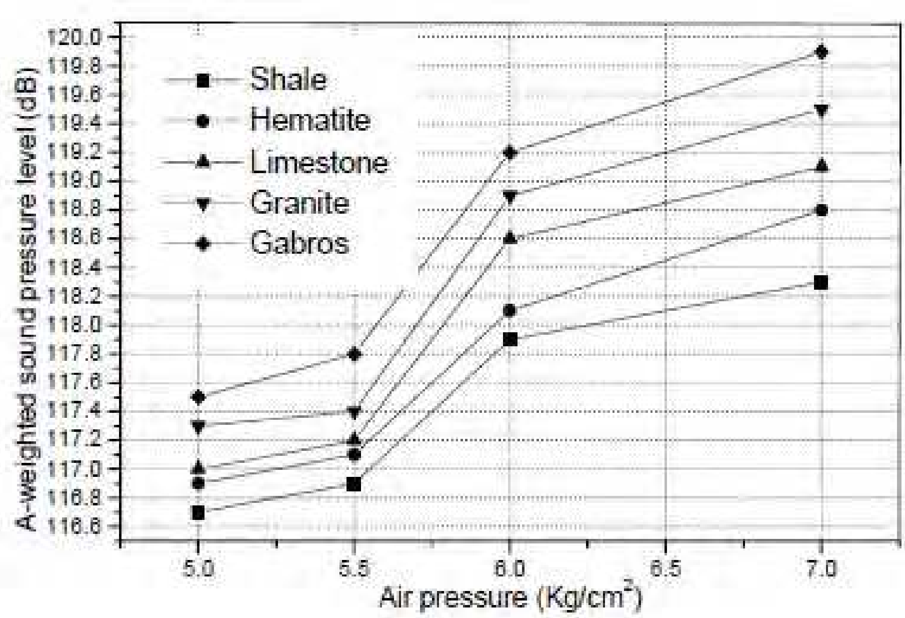

Fig. 4. Effect of air pressure on sound level at the operator's position at a constant thrust of 160 N for different rock blocks

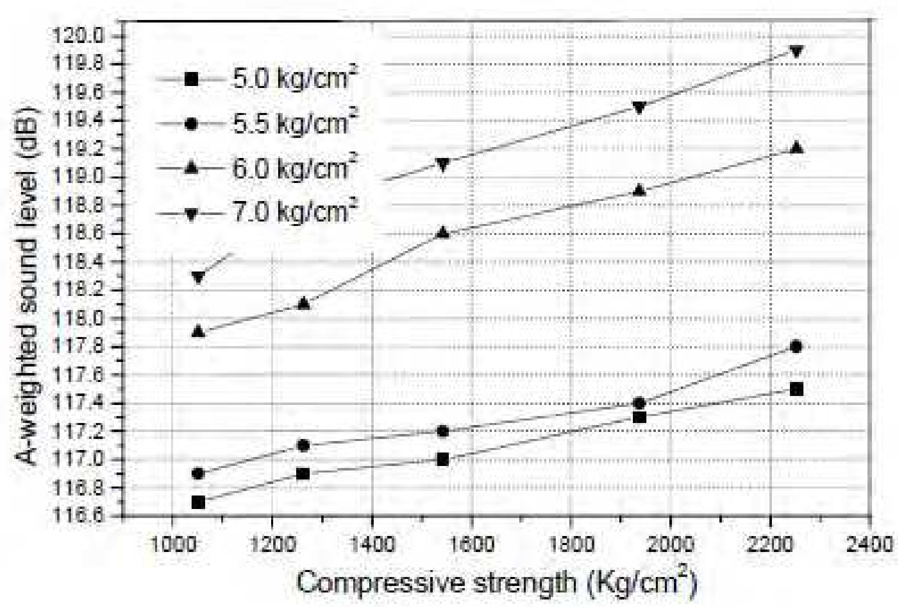

Fig. 5. Effect of compressive strength of rock on sound levels at the operator position for a constant thrust of 160 N and different air pressures

b. At exhaust

The L_{eq} level at exhaust for different rocks of varying strength at various thrusts and air pressures are given in Table 4. A significant increase in the sound level with an increase in the compressive strength and a decrease in the abrasivity is observed for different rocks. For instance, the difference in A-weighted sound level for block-1 and block-5 is 2.2 dB at constant air pressure and thrust of 5 kg/cm^2 and 160 N respectively. The variation of sound levels in all the five blocks, each with a different compressive strength and abrasivity, at an air pressure of 5 kg/cm^2 and thrust varying from 160 to 360 N is shown in Fig.6.

It can be seen that, with an increase in the compressive strength and a decrease in the abrasivity of rocks, the L_{eq} level increased near the exhaust at each thrust level for a constant air pressure of 5 kg/cm^2. Similar results can be seen from Table 4, for air pressures of 5.5, 6.0 and 7.0 kg/cm^2. At an air pressure of 5 kg/cm^2, an increase in thrust by 200 N (from 160 to 360 N) caused the sound level difference to vary from 1.4 to 1.8 dB for different rocks at the exhaust. The effect of compressive strength of rock on sound level at exhaust for a constant thrust of 160 N for different air pressure values is shown in Fig. 7. An increase in the air pressure by 2 kg/cm^2 at a constant thrust of 160 N resulted in an increase in the sound level, varying from 1.2 to 2.4 dB for different rock properties. This shows that, both thrust and air pressure have a significant effect on sound level produced by pneumatic drill at the exhaust.

Air pressure (kg/cm²)	Thrust (N)	Shale	Hematite	Limestone	Granite	Gabros
5	160	118.4	118.7	119.8	120.1	120.6
	200	118.8	119.2	120.6	120.9	121.5
	300	119.3	119.5	121.0	121.6	121.7
	360	119.9	120.5	121.5	121.9	122.2
5.5	160	119.9	120.1	120.2	120.7	120.8
	200	120.2	120.7	120.9	121.2	121.7
	300	120.9	121.3	121.7	121.9	122.3
	360	121.2	121.7	121.8	122.2	122.6
6	160	120.3	120.5	120.8	121.1	121.4
	200	120.6	121.2	121.8	122.2	122.5
	300	121.9	122.5	122.9	123.4	123.8
	360	121.8	122.8	123.2	123.7	124.2
7	160	120.8	120.9	121.2	121.5	121.8
	200	121.3	121.5	121.9	122.4	122.7
	300	122.0	122.7	123.2	123.7	123.9
	360	122.5	123.1	123.7	123.9	124.5

Table 4. L_{eq} level at exhaust for different rocks at various thrust and air pressures

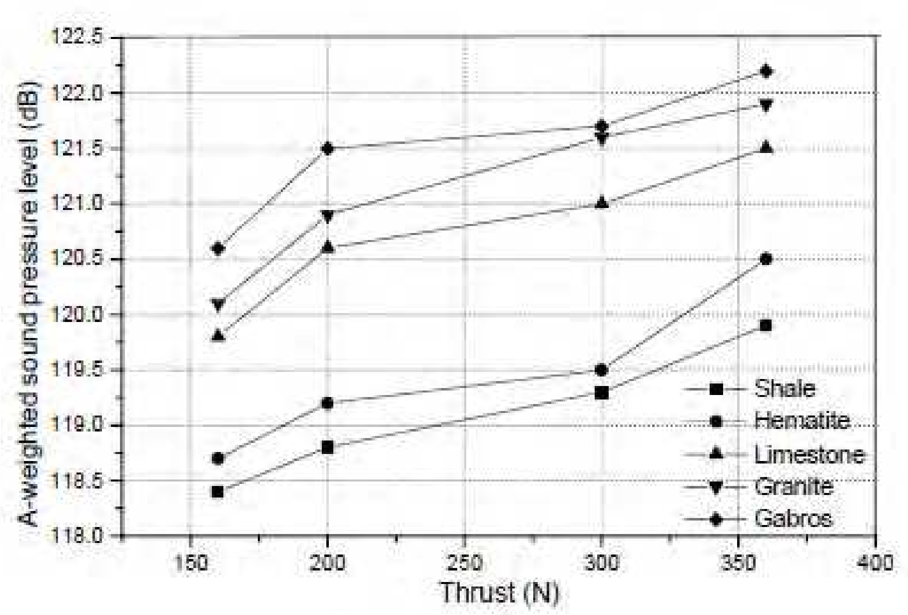

Fig. 6. Effect of thrust on sound level at the exhaust at constant air pressure of 5 kg/cm² for different rock blocks

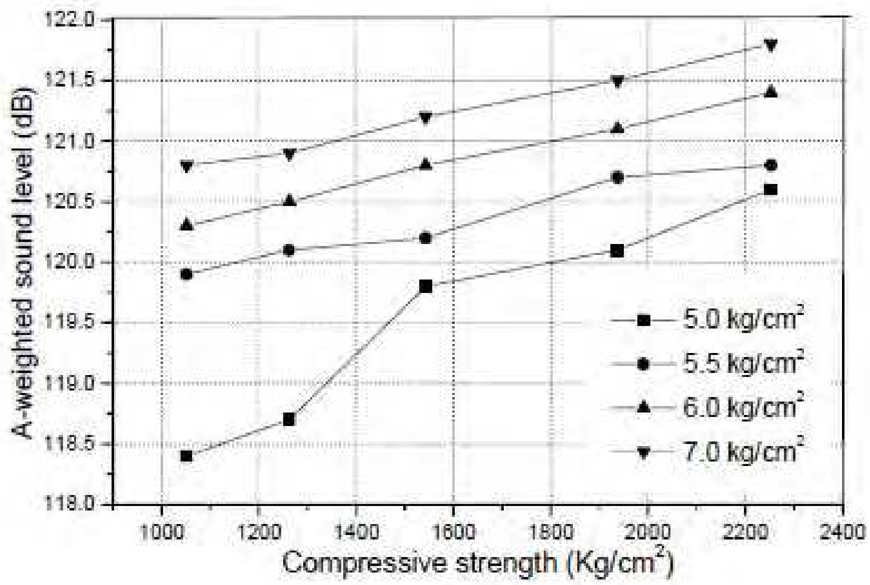

Fig. 7. Effect of compressive strength of rock on sound levels at exhaust at a constant thrust of 160 N and varying air pressure

c. Near drill rod

The L_{eq} level near the drill rod for rocks having varying compressive strength and abrasivity at various thrusts and air pressures is given in Table 5. Maximum increase in the sound level with an increase in the compressive strength and a decrease in the abrasivity was observed near the drill rod compared to that of other positions.

Air pressure (kg/cm²)	Thrust (N)	Shale	Hematite	Limestone	Granite	Gabros
5	160	120.5	121.9	122.3	122.8	123.3
	200	121.2	122.4	123.0	123.4	123.9
	300	122.0	122.7	123.4	124.1	124.2
	360	122.7	123.3	123.7	124.4	125.0
5.5	160	121.1	122.2	122.7	123.1	123.4
	200	121.9	122.8	123.5	123.9	124.1
	300	122.4	123.5	124.2	124.5	124.7
	360	122.9	123.9	124.5	124.8	125.3
6	160	121.7	122.8	123.1	123.5	123.8
	200	122.3	123.1	123.8	124.2	124.5
	300	122.8	123.9	124.6	124.9	125.3
	360	123.2	124.2	124.9	125.3	125.7
7	160	123.1	123.7	123.9	124.2	124.8
	200	123.7	124.2	124.9	125.0	125.5
	300	124.5	125.5	125.2	126.2	126.7
	360	124.9	125.7	125.8	126.7	126.9

Table 5. L_{eq} level near the drill rod for different rocks at various thrusts and air pressures

The sound level difference at an air pressure of 5 kg/cm² with increase in thrust from 160 to 360 N varied from 2.2 to 2.8 dB. At air pressures of 5.5, 6.0 and 7.0 kg/cm², this sound level difference of shale and gabro varied from 2.2 to 2.4 dB, 2.1 to 2.5 dB and 1.7 to 2.2 dB respectively. The above results clearly indicate that the variation in the compressive strength and abrasivity of rock has a significant effect on the sound level near the drill rod and that the sound level near the drill rod increases as the compressive strength increases.

Both the air pressure and thrust were observed to have a significant effect on the sound level produced near the drill rod. For instance, an increase in the air pressure by 2 kg/cm², at a constant thrust of 160 N caused an increase in the sound level varying from 1.4 to 2.6 dB. Similarly, an increase in the sound level with an increase in the thrust of 200 N at an air pressure of 5 kg/cm² varied from 1.4 dB to 2.2 dB for rocks having varying properties.

The effect of the compressive strength of rock on the sound level near the drill rod at a constant thrust of 160 N and varying air pressure is shown in Fig. 8.

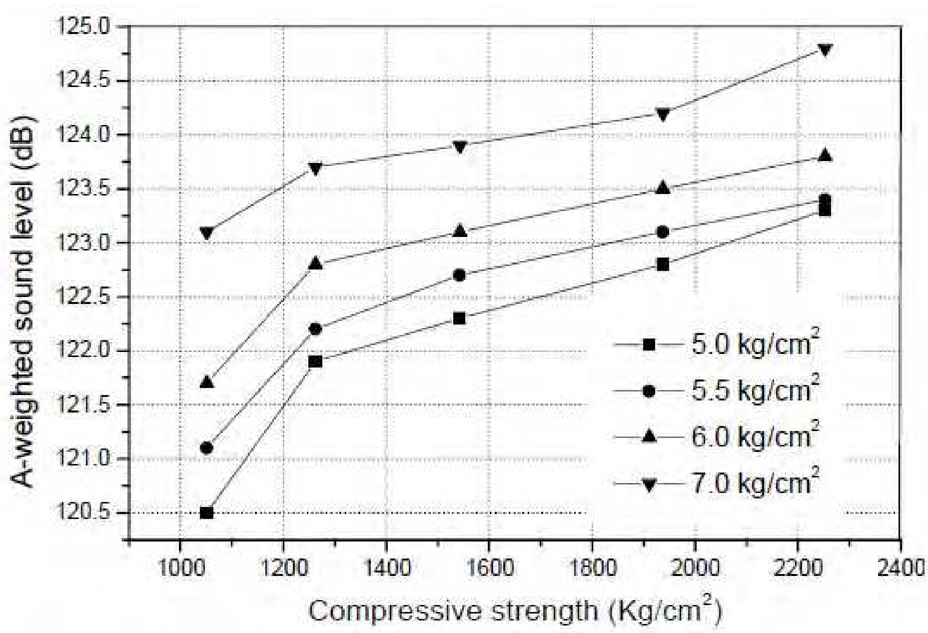

Fig. 8. Effect of compressive strength of rock on sound levels near drill rod for a constant thrust of 160 N and varying air pressure

d. Near the drill bit

The L_{eq} level near the drill bit for rocks having varying compressive strength and abrasivity at various thrusts and air pressures is given in Table 6. In general, an increase in the sound level is observed at each thrust and air pressure with an increase in the compressive strength and a decrease in the abrasivity of the rocks. The difference in the sound level at an air pressure of 5 kg/cm² and with an increase in the thrust from 160 to 360 N varied from 0.9 to 1.9 dB. At air pressures of 5.5, 6.0 and 7.0 kg/cm², this sound level difference in different rocks varied from 1.2 to 2.1 dB. This shows that an increase in the compressive strength and a decrease in the abrasivity of rock increase the sound level significantly.

In this case also, both air pressure and thrust were observed to have a significant effect on the sound level. For example, an increase in the air pressure by 2 kg/cm² at a constant thrust of 160 N indicated an increase in the sound level of 1.7 dB for block-1 and 1.0 dB for block-2 to block-5.

Air pressure (kg/cm²)	Thrust (N)	Shale	Hematite	Limestone	Granite	Gabros
5	160	120.0	121.0	121.2	121.6	121.9
	200	120.8	121.5	121.7	122.0	122.3
	300	121.5	122.0	122.1	122.3	122.5
	360	121.8	122.1	122.3	122.5	122.7
5.5	160	120.8	121.2	121.6	121.8	122.2
	200	121.3	121.7	122.2	122.5	122.7
	300	121.6	122.3	122.7	122.9	122.9
	360	121.9	122.6	122.9	123.3	123.7
6	160	121.5	121.7	122.0	122.4	122.7
	200	121.8	121.9	122.3	122.7	122.9
	300	122.3	122.6	122.9	123.2	123.6
	360	122.7	122.8	123.2	123.7	123.9
7	160	121.7	122.0	122.2	122.5	122.9
	200	121.9	122.4	122.7	122.9	123.1
	300	122.7	123.1	123.6	123.9	124.8
	360	122.9	123.5	123.8	124.0	124.9

Table 6. L_{eq} level near the drill bit for different rocks at various thrust and air pressures

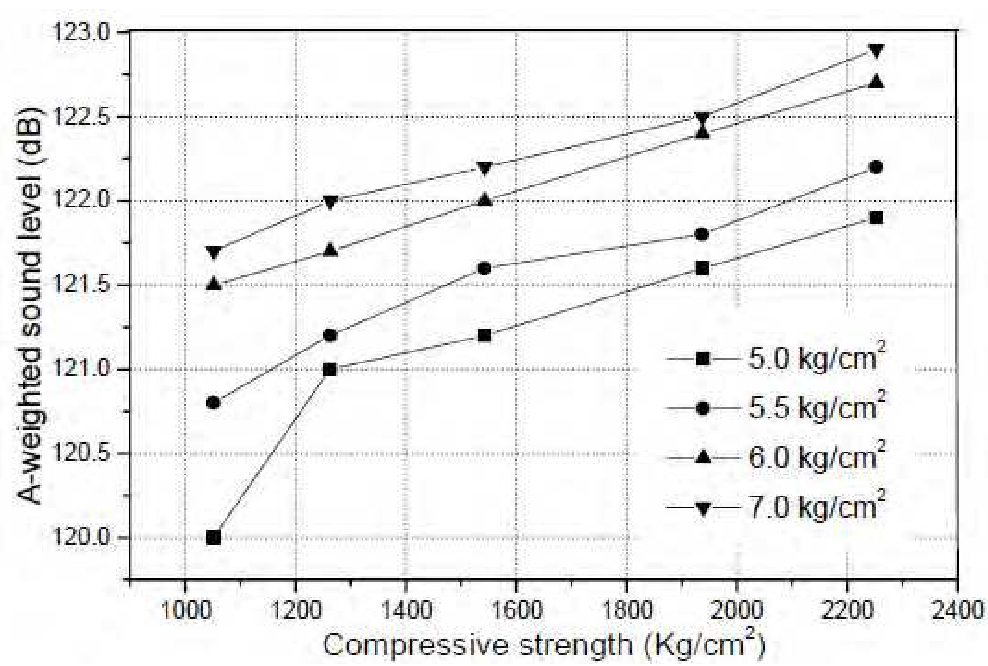

Fig. 9. Effect of compressive strength of rock on sound levels near the drill bit for a constant thrust of 160 N and varying air pressure

The increase in the sound level with an increase in the thrust of 200 N at an air pressure of 5 kg/cm² was 1.8 dB for shale, 1.1 dB for hematite and limestone, 0.9 dB for granite and 0.8 dB for gabro. The effect of compressive strength of rock on the sound level near the drill bit for a constant thrust of 160 N for different air pressure values is shown in Fig. 9.

2.2 Laboratory investigations using CNC machine

Compressor was one of the major sources of noise in the laboratory investigation explained in section 2.1. To overcome this, and also to nullify background noise, another investigation was carried out using Computer Numerical Controlled (CNC) machine with carbide drill bit setup. Further, the main aim of this investigation was to find out the relationship of rock properties with sound level produced during drilling.

2.2.1 Experimental setup

In the laboratory, rock drilling operations were performed on BMV 45 T20, Computer Numerical Controlled (CNC) vertical machining centre. The experimental set-up was in a fibre and glass–paned room of 5 m width, 6 m length and 9 m height. The important specifications of the CNC machine used were:

- Table size 450 mm x 900 mm
- Recommended optimum air pressure – 6 bar.
- Power supply – 415V, 3Phase, 50Hz

Carbide drill bits of shank length 40 mm and diameters of 6, 10, 16 and 20 mm were used for drilling operation. The machine was set to drill 30 mm drillhole length. Since the drilling method affects the sound produced, an attempt was made to standardize the testing procedure. Throughout the drilling process a relatively constant rotation speed (RPM), and penetration rate (mm/min) were provided in order to obtain consistent data.

2.2.2 Rock samples used in the investigation

For this investigation, different igneous rocks were collected from different localities of India taking care of representation of variety of strength. During sample collection, each block was inspected for macroscopic defects so that it would provide test specimens free from fractures and joints. The different igneous rocks used in the investigation and their properties are given in Table 7.

2.2.3 Instrumentation for noise measurement

The instrument used for sound measurement was a Spark 706 from Larson Davis, Inc., USA. The instrument was equipped with a detachable 10.6 mm microphone and 7.6 cm cylindrical mast type preamplifier. The microphone and preamplifier assembly were connected by an integrated 1.0 m cable. A Larson Davis CAL 200 Precision Acoustic Calibrator was used for calibrating the sound level meter. Before taking any measurement, the acoustical sensitivity of the sound level meter was checked using the calibrator.

2.2.4 Determining the rock properties

a. Uniaxial compressive strength

Compressive strength is one of the most important mechanical properties of rock material, used in blast hole design. To determine the UCS of the rock samples, 54 mm diameter NX-size core specimens, having a length-to-diameter ratio of 2.5:1 were prepared as suggested by ISRM. Each block was represented by at least three core specimens. The oven-dried and NX-size core specimens were tested by using a microcontroller compression testing machine. The average results of uniaxial compressive strength values of different rocks are given in Table 7.

Sl. No.	Rock Sample	UCS (MPa)	Dry Density (g/cc)	Tensile Strength (MPa)	A–weighted Equivalent Sound level Leq (dB)	
					Min L_{eq}	Max L_{eq}
1	Koira Grey Granite	77.8	2.773	9.60	112.4	118.1
2	Quartz monzonite	42	2.556	4.72	93.9	97.6
3	Granodiorite	79.6	2.481	9.83	113.1	118.9
4	Peridotite	64.9	2.649	7.82	107.7	112.4
5	Serpentine	37	2.512	4.16	90.7	93.8
6	Syenite	47	2.536	5.28	96.6	100.1
7	Norite	48.7	2.558	5.47	97.5	100.9
8	Granite Porphyry	51.2	2.766	6.17	99.1	102.9
9	Pegmatite	35.4	2.496	3.98	90.0	94.2
10	Charnockite	66.8	2.699	8.05	109.0	114.1
11	Diorite Porphyry	57.2	2.615	6.89	104.0	108.3
12	Grey Granite	46.4	2.571	5.21	95.8	99.6
13	Dolerite	66.1	2.665	7.96	107.9	112.8
14	Gabbro	102.2	3.168	12.62	118.2	121.3

Table 7. Rock properties and range of A–weighted equivalent sound level values obtained during drilling of igneous rocks.

b. Dry density

Density is a measure of mass per unit of volume. Density of rock material varies, and often related to the porosity of the rock. It is sometimes defined by unit weight and specific gravity. The density of each core sample was measured after the removal of moisture from it. The moisture was removed by placing the samples in an electric oven at about 80^0 C for one hour and they were dried at room conditions. The density data of dry samples was obtained from the measurements of bulk volume and mass of each core using the following formula.

$$\rho(g/cc) = \frac{Mass\,of\,sample}{Volume\,of\,sample}$$

Each test was repeated five times and the average values were recorded. The average results of dry densities of different rocks are given in Table 7.

c. Tensile strength

Rock material generally has a low tensile strength. The low tensile strength is due to the existence of micro cracks in the rock. The existence of micro cracks may also be the cause of rock failing suddenly in tension with a small strain. Tensile strength of rock is obtained from Brazilian test. To determine the Brazilian tensile strength of the rock samples, 54 mm diameter NX-size core specimens, having a length less than 27mm were prepared as suggested by

ISRM. The cylindrical surfaces were made free from any irregularities across the thickness. End faces were made flat to within 0.25 mm and parallel to within 0.25°. The specimen was wrapped around its periphery with one layer of the masking tape and loaded into the Brazil tensile test apparatus across its diameter. Loading was applied continuously at a constant rate such that failure occured within 15-30 seconds. Ten specimens of the same sample were be tested. The average results of Brazilian tensile strength of different rocks are given in Table 7.

2.2.5 Noise measurement

Test samples for rotary drilling, having a dimension of 20 cm x 20 cm x 20 cm were prepared by sawing from block samples. During drilling, to overcome the vibration of rock block, it was firmly held by vise which is kept on the table of the machine. Sound level measurements were carried out for rotation speeds of 150, 200, 250 and 300 RPM and penetration rates of 2, 3, 4 and 5 mm/min on each rock block.

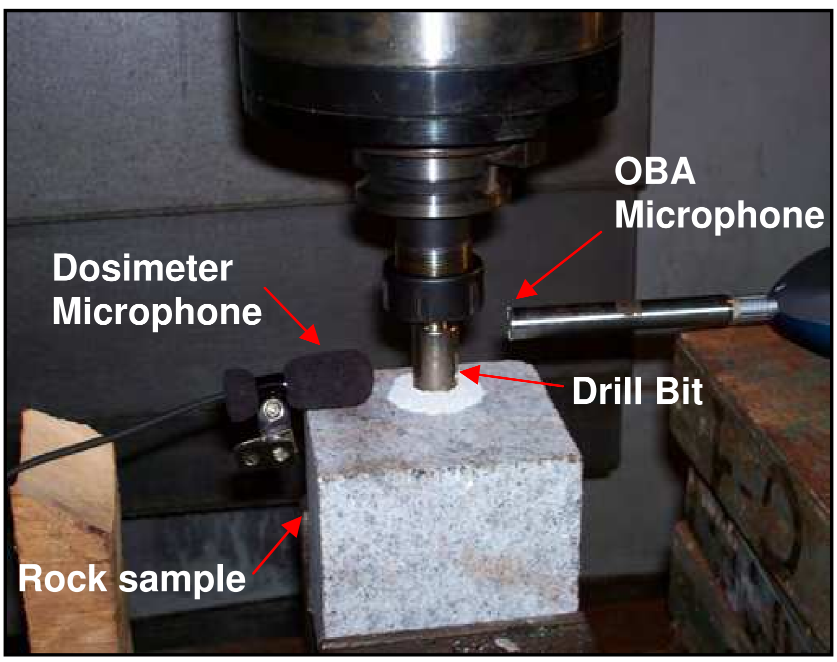

Fig. 10. Position of microphone from drill setup.

For each combination of drill bit diameter, drill bit speed and penetration rate, a total of 64 sets of test conditions were arrived at (drill bit diameter of 6, 10, 16 and20 mm; drill bit speed of 150, 200, 250 and 300 RPM; penetration rate of 2, 3, 4and 5 mm/min). A-weighted equivalent continuous sound level (Leq) was recorded for all 64 different drill holes of 30 mm depth on each rock block. For all measurements, the sound level meter was kept at a distance of 1.5 cm from the periphery of the drill bit (Fig. 10).

For a particular condition and for the same rock block, the sound level was determined five times in relatively rapid succession. It was found that the recorded equivalent sound levels were almost consistent. The arithmetic average of each set of five measurements was computed to yield an average A-weighted equivalent sound level for a particular condition.

For 15 minutes, the sound level was measured at 1.5 cm from the drill bit without drilling. The equivalent sound level of 65.2 dB was recorded without drilling which was mainly due to the noise of the CNC machine.

It may be argued that sound produced from the CNC machine itself may affect the sound level measurement during rock drilling. It is important to mention here that if the sound level difference between two sources is more than 10 dB, then the total sound level will remain the same as that of the higher source. Further, taking the measurement very close to the source will reduce the effect of sound produced from other sources.

2.2.6 Regression modelling and analysis of variance (ANOVA)

The results of the measurements of rock properties (UCS, dry density, tensile strength) and range (maximum and minimum) of A–weighted equivalent sound level recorded during drilling of igneous rocks are given in Table 7. These results were analysed using Multiple Regression and Analysis of Variance (ANOVA) technique. For analysis Minitab 15 software for windows was used.

To obtain applicable and practical predictive qualitative relationships it is necessary to model the physico-mechanical rock properties and the drill process variables. These models will be of great use during the optimization of the process. The experimental results were used to model the various responses using multiple regression method by using a non-linear fit among the responses and the corresponding significant parameters. Multiple regression analysis is practical, relatively easy for use and widely used for modelling and analyzing the experimental results. The performance of the model depends on a large number of factors that act and interact in a complex manner. The mathematical modelling of sound level produced during drilling is influenced by many factors. Therefore a detailed process representation anticipates a second order model. ANOVA was carried out to find which input parameter significantly affects the desired response. To facilitate the experiments and measurement, four important factors are considered in the present study. They are drill bit diameter in mm (A), drill bit speed in RPM (B), penetration rate in mm/min (C) and equivalent sound level produced during drilling in dB (D). The responses considered are UCS, Dry Density and Tensile Strength. The mathematical models for the physico- mechanical properties with parameters under consideration can be represented by $Y = f(x_1, x_2, x_3, \ldots) + \in$, where Y is the response and x_1, x_2, x_3, are the independent process variables and Є is fitting error. A quadratic model of f can be written as $f = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ij} x_i^2 + \sum_{i<j}^{n} a_{ij} x_i x_j + \in$ where a_i represents the linear effect of x_i, a_{ij} represents the quadratic effect of x_i and a_{ij} reveals the linear interaction between x_i and x_j. Then the response surface contains linear terms, squared terms and cross product terms.

In order to compare all reasonable regression models, a backward elimination procedure was used as the screening procedure. Then the independent variable having the absolute smallest t statistic was selected. If the t statistic was not significant at the selected α (to test the significance, one needs to set a risk level called the alpha level. In most cases, the ''rule of thumb'' is to set the alpha level at 0.05, i.e., 95% confidence interval) level, the independent variable under consideration was removed from the model and the regression analysis was performed by using a regression model containing all the remaining independent variables. If the t statistic was significant, the model was selected. The procedure was continued by removing one independent variable at a time from the model. The screening was stopped when the independent variable remaining in the model could not be removed from the system.

For UCS, the best model found was

$$UCS = 468.204 + 2.225\times A + 0.069\times B + 2.502\times C - 10.273\times D + 0.061\times D^2$$
$$- 0.025\times A\times D - 0.001\times B\times D - 0.028\times C\times D$$

Significance of regression coefficients for estimation of Universal Compressive strength using Minitab 15 software is listed in Table 8a. The final ANOVA table of the reduced quadratic model for UCS is shown in Table 8b. In addition to the degrees of freedom (DF), mean square (MS), t-ratio and p values associated with factors are represented in this table. As seen form Table 8c, the selected model explains 97.45% of the total variation in the observed UCS tests.

Model terms for UCS	Parameter estimate (coefficients)	t	p
Constant	468.204	22.692	0.000
A	2.225	8.048	0.000
B	0.069	2.671	0.008
C	2.502	1.948	0.032
D	-10.273	-26.767	0.000
D^2	0.061	33.119	0.000
AD	-0.025	-9.465	0.000
BD	-0.001	-3.149	0.002
CD	-0.028	-2.294	0.022

Table 8a. Significance of regression coefficients for estimation of Universal Compressive strength using Minitab 15 software.

For UCS the p-values for all the independent variables are less than 0.05 showing statistical significance. In addition to this the p value of D^2 term and interaction terms related to A, B, C with D are less than 0.05 which establishes the experimental results.
Experimental analysis also shows that for igneous rocks, as the UCS increases the sound level produced during drilling also increases.
Fig. 11 shows the variation between experimentally measured UCS with the UCS calculated from the developed regression model for test data.

Source of variations	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	p - Value
Model	8	221064.60	27633.07	3055.87	0.000
Linear	4	6850.91	1712.73	189.41	0.000
Square	1	9918.64	9918.64	1096.88	0.000
Interaction	3	936.54	312.18	34.52	0.000
Residual Error	631	5705.90	9.04		
Total	639	226770			

Table 8b. Analysis of variance (ANOVA) for the selected quadratic model for estimation of UCS.

R^2	Predicted R^2	Adjusted R^2	Standard error
0.9748	0.9739	0.9745	3.00710

Table 8c. Model summary for dependent variable (UCS)

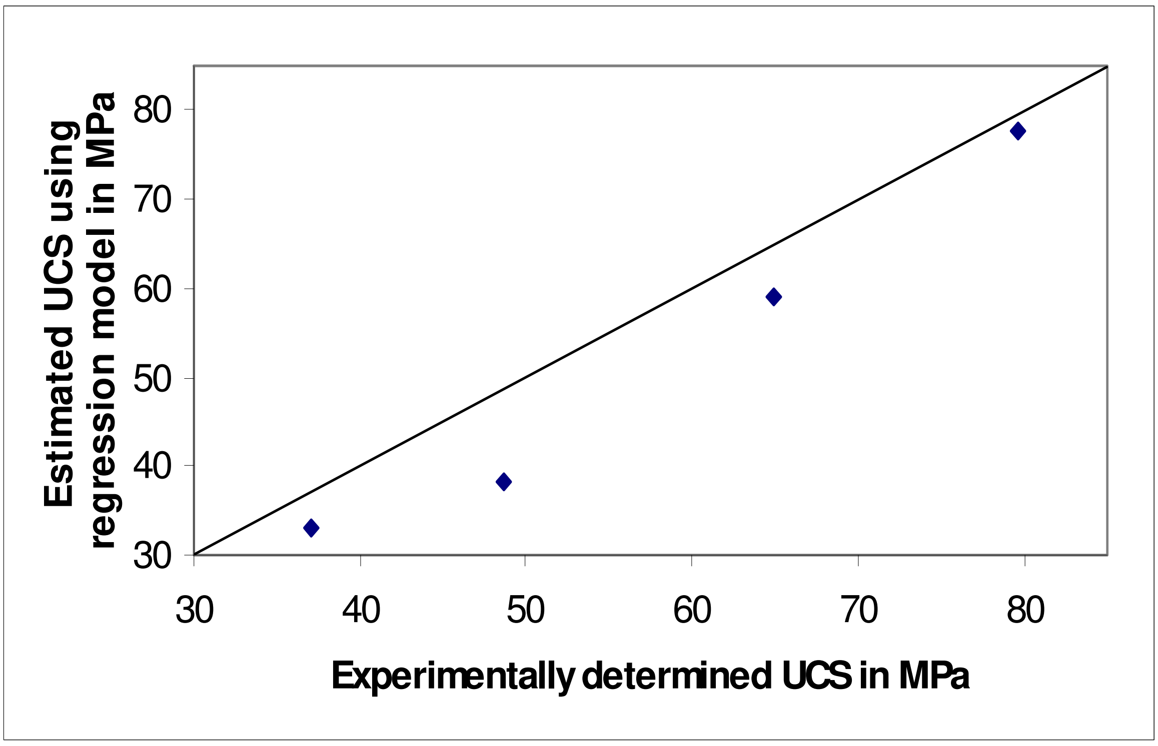

Fig. 11. Estimated UCS using Regression Vs Experimentally determined UCS model of Test data

For Dry Density, the best model found was

$$\rho = 11.0892 + 0.0387 \times A - 0.1813 \times D + 0.0010 \times D^2 - 0.0008 \times A \times D$$

Significance of regression coefficients for estimation of Dry density are listed in Table 9a. The final ANOVA table of the reduced quadratic model for Dry density is shown in Table 9b. In addition to the degrees of freedom (DF), mean square (MS), t-ratio and p values associated with factors are represented in this table. As seen form Table 9c, the selected model explains 77.53% of the total variation in the observed dry density tests.

Model terms for Dry Density	Parameter estimate (coefficients)	t	p
Constant	11.0892	19.120	0.000
A	0.0387	4.814	0.000
D	-0.1813	-16.284	0.000
D^2	0.0010	17.966	0.000
AD	-0.0004	-5.205	0.000

Table 9a. Significance of regression coefficients for estimation of dry density using Minitab 15 software.

Source of variations	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	p - Value
Model	4	16.93505	4.23376	552.05	0.000
Linear	2	2.06246	1.03123	134.47	0.000
Square	1	2.47550	2.47550	322.79	0.000
Interaction	1	0.20780	0.20780	27.10	0.000
Residual Error	635	4.86991	0.00767		
Total	639	21.8050			

Table 9b. Analysis of variance (ANOVA) for the selected quadratic model for estimation of dry density.

R^2	Predicted R^2	Adjusted R^2	Standard error
0.7767	0.7729	0.7753	0.0875737

Table 9c. Model summary for dependent variable (dry density)

For Dry density the p-values for independent variables A and D are less than 0.05 showing statistical significance. In addition to this the p value of D^2 term and interaction terms related to A with D are less than 0.05 which establishes the experimental results.
Fig. 12 shows the variation between experimentally measured density with the density calculated from the developed regression model for test data.

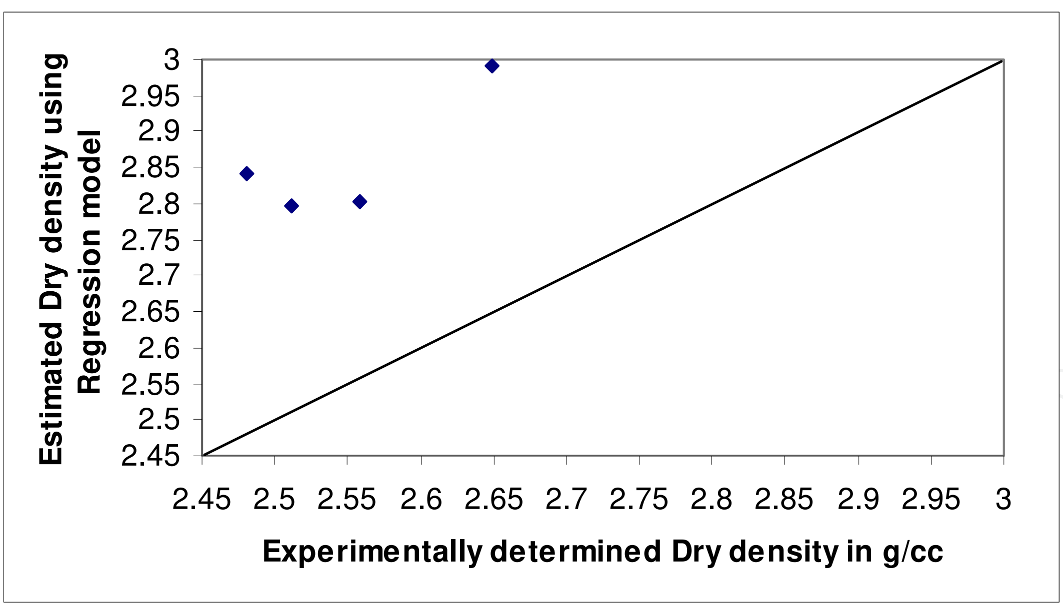

Fig. 12. Estimated dry density using Regression model Vs Experimentally determined dry density of Test data

For Tensile Strength, the best model found was

$$TS = 56.4706 + 0.2730 \times A + 0.0086 \times B + 0.3106 \times C - 1.2657 \times D + 0.0076 \times D^2 - 0.0031 \times A \times D - 0.0001 \times B \times D - 0.0035 \times C \times D$$

Significance of regression coefficients for estimation of tensile strength is listed in Table 10a. The final ANOVA table of the reduced quadratic model for tensile strength is shown in Table 10b. In addition to the degrees of freedom (DF), mean square (MS), t-ratio and p values associated with factors are represented in this table. As seen form Table 10c, the selected model explains 97.88 % of the total variation in the observed tensile strength tests.

Model terms for Tensile Strength	Parameter estimate (coefficients)	t	p
Constant	56.4706	22.778	0.000
A	0.2730	8.219	0.000
B	0.0086	2.768	0.006
C	0.3106	2.012	0.045
D	-1.2657	-27.448	0.000
D^2	0.0076	34.392	0.000
AD	-0.0031	-9.783	0.000
BD	-0.0001	-3.295	0.001
CD	-0.0035	-2.394	0.017

Table 10a. Significance of regression coefficients for estimation of tensile strength using Minitab 15 software.

For Tensile Strength the p-values for all the independent variables are less than 0.05 showing statistical significance. In addition to this the p value of D^2 term and interaction terms related to A, B and C with D are less than 0.05 which establishes the experimental results.

Source of variations	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	p - Value
Model	8	3855.630	481.954	3691.64	0.000
Linear	4	104.024	26.006	199.20	0.000
Square	1	154.417	154.417	1182.80	0.000
Interaction	3	14.491	4.830	37.00	0.000
Residual Error	631	82.379	0.131		
Total	639	3938.01			

Table 10b. Analysis of variance (ANOVA) for the selected quadratic model for estimation of tensile strength.

R^2	Predicted R^2	Adjusted R^2	Standard error
0.9791	0.9783	0.9788	0.361321

Table 10c. Model summary for dependent variable (tensile strength)

Fig. 13 shows the variation between experimentally measured tensile strength with the tensile strength calculated from the developed regression model for test data.

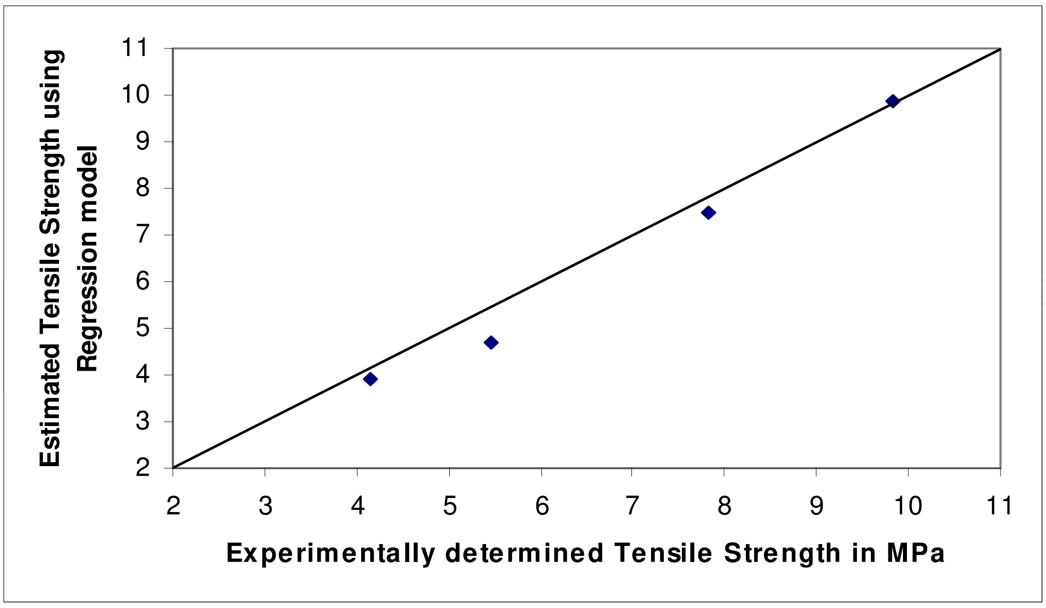

Fig. 13. Estimated tensile strength using Regression model Vs Experimentally determined tensile strength of Test data

3. Field investigations

An attempt was also made to experimentally determine the UCS in the field during drilling blast holes. The Medapalli Open Cast Project (MOCP), belonging to M/S Singareni Colliery Company Limited, situated in the state of Andhra Pradesh in India was used for the field investigations. The rock stratum at the MOCP consists primarily of sandstone, carbonaceous shale, sandy shale, coal, shale, shaly coal, carbonaceous sandstone, and carbonaceous clay. There were a total of five coal seams in that area. Out of these five seams, four coal seams from the top had already been extracted. Borehole data near the investigation area are shown in Fig. 14, which were obtained from the Geology section of the mine. The lithological details from the 4^{th} to 5^{th} seam are also indicated in Fig. 14 (right hand side of the figure), with the depth of each rock formation.

Between the 4^{th} and 5^{th} seam, the strata are classified into Upper Roof (3.0–6.0 m above the top of the coal seam i.e. top of 5^{th} seam), Immediate Roof (0.0–3.0 m above the top of the coal seam), Immediate Floor (0.0–3.0 m below the base of the coal seam), Main Floor (3.0–6.0 m below the base of the coal seam) and Interburden (bounding strata not classified as roof or floor). The details are shown in Fig. 14.

3.1 Noise measuring instruments

The instruments described in section 2.1.3 and 2.2.3 were again used for field investigations. A rotary drill machine was used for drilling blast holes in the mine. The drill bit diameter was 150.0 mm with tungsten carbide button bits. Air was used as the flushing fluid. Compressed air was used as the feed mechanism with a sump pressure of 1.275 MPa and a line pressure of 1.373 MPa.

Both dosimeter and one-third-octave-band analyser were used to record the sound level. For all measurements, both the dosimeter and one-third-octave-band analyser were hand-held at a height of 1.0 m from the ground level and at a distance of 1.5 m and 2.5 m from the blast

hole (Fig. 15). Sound levels were recorded for 16 different drill holes. At each second, the equivalent continuous A-weighted sound levels were recorded by the dosimeter. To determine the sound level spectrum, the one-third-octave-band analyser was set to measure A-weighted, time-averaged one-third-octave-band sound levels with nominal mid-band frequencies from 25 Hz to 20 kHz. For each measurement, the one-third-octave-band analyser was set for an averaging time of 2 min. The data recorded during field measurements using the dosimeter and one-third-octave-band analyser were downloaded to the computer for analysis. Some critical observations, such as colour change of flushing dust and the exact time during colour change were also recorded.
For the same drill diameter and type, penetration rate and weight on bit, the sound levels were measured for various drilled holes consisting of strata of different compressive strengths.
For about 3 min, the sound level at about 1.5 m from the drill rod was measured without drilling. The sound level measured without drilling was mainly due to the compressor operating near the drilling machine.

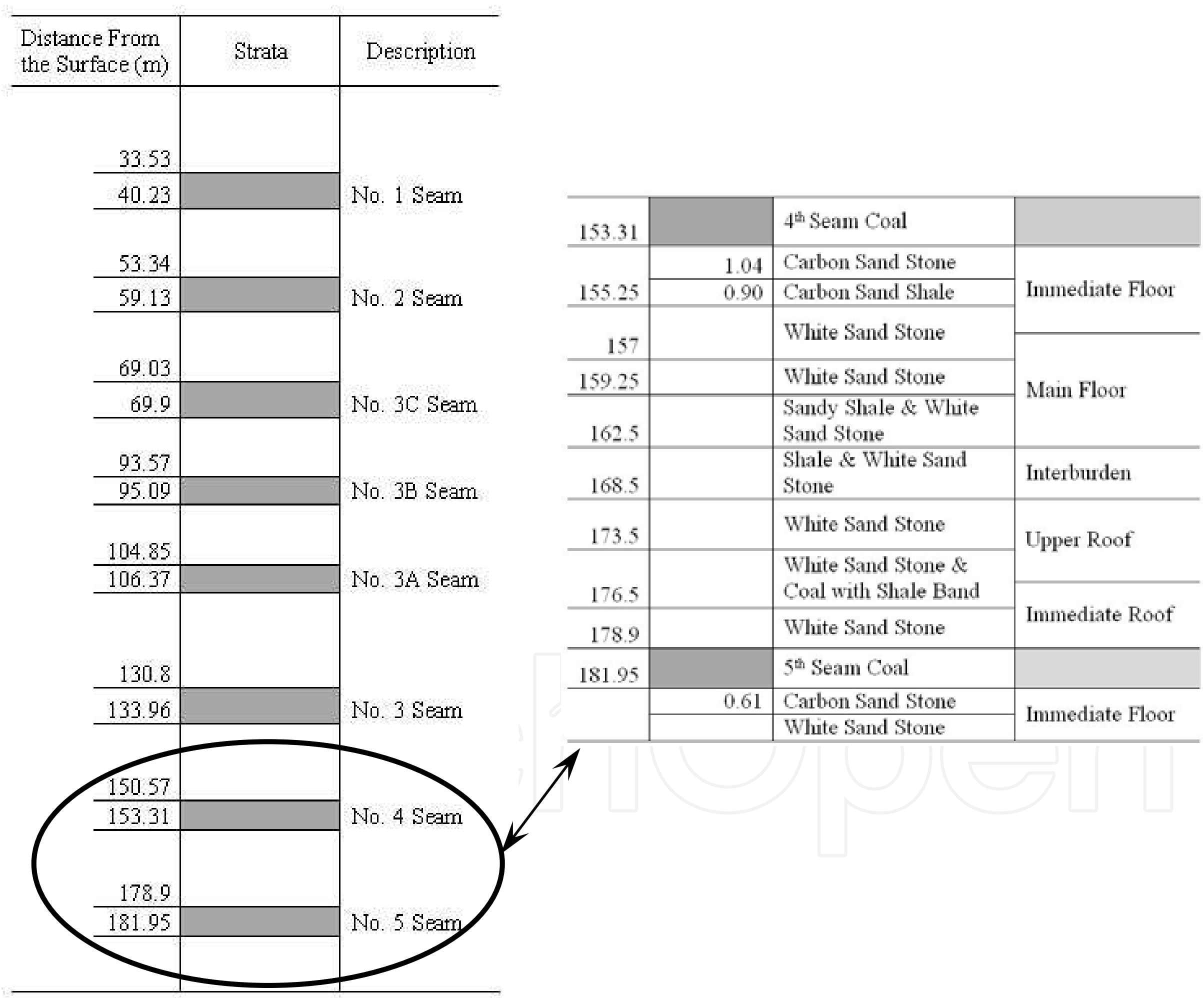

Fig. 14. Lithology of the area (Bore hole data)

3.2 Sound measurement

Field investigation of the sound levels produced during drilling was carried out on the rotary drill machine described in Section 3.1. All the measurements were carried out while drilling blast holes. During field investigation, bit type and diameter, blast hole length, weight on bit, compressed air pressure, net drilling time and rpm of the drill bit were recorded. The penetration rate (m/min) was calculated from the drilled hole length (metres) and the net drilling time (minutes). Blast holes were drilled between the 4th and 5th seams at each classified strata (Fig. 14). Depending on the blast design, the blast hole length was limited to 6.0 m, whereas at other places it was only 3.0 m. For 3.0 m long blast hole, the weight on the bit was 12.0 kg, whereas for the 6.0 m long holes, the weight on the bit was 8.0 kg. The exploratory borehole data were collected from the Geology section of the mine. The UCS, density, tensile strength, young's modulus and impact strength of various strata were collected from the exploratory borehole data near the blast hole drilling as given in Table 11.

Fig. 15. Sound measurement during drilling

3.3 Results of investigation using dosimeter

Using dosimeter, L_{eq} was measured for each second. Drill bit penetration rate in m/sec was calculated. The time taken to drill 3.0 m deep hole was noted down. Then L_{eq} vs drill hole depth was plotted and is as shown in Fig. 16 and Fig. 17.

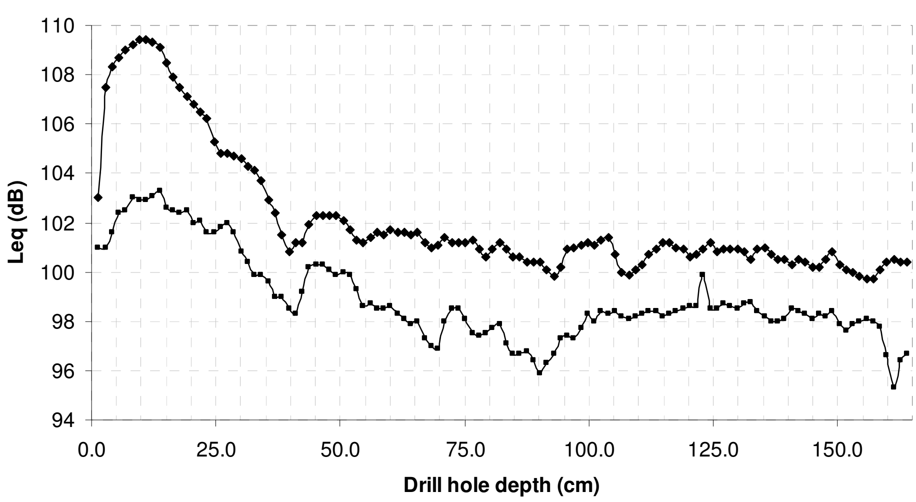

Fig. 16. L_{eq} vs drill hole depth with 8.0 kg weight on drill bit: ♦ Blast hole–1 (UCS 36.49 MPa); ■ Blast hole–12 (UCS 28.35 MPa).

Drill Hole No.	Strata Location	Distance from surface in (m)	Formation	Drill Bit diameter (mm)	Weight on bit (kg)	Drill rod RPM	Observation Distance (m)	Penetration Rate (m/min)	Density (g/cc)	Tensile Strength (MPa)	Compressive Strength (MPa)	Young's Modulus (GPa)	Impact Strength Number
1	Immediate Floor of 4th seam	155.25 to 159.25	White Sand Stone	150	8	85	1.5	0.82	2.28	2.62	36.49	5.10	52.02
2	Interburden between 4&5 seam	162.5 to 168.5	Shale & White Sand Stone	150	12	73	1.5	1.00	2.24	2.36	30.61	3.83	49.42
3	Interburden between 4&5 seam	162.5 to 168.5	Shale & White Sand Stone	150	12	73	2.5	1.00	2.24	2.36	30.61	3.83	49.42
4	Upper Roof of 5th seam	173.5 to 176.5	White Sand Stone & Coal with shale band	150	12	73	4.5	1.00	2.22	1.98	28.84	3.01	47.80
5	Upper Roof of 5th seam	173.5 to 176.5	White Sand Stone & Coal with shale band	150	12	73	3.5	1.00	2.22	1.98	28.84	3.01	47.80
6	Upper Roof of 5th seam	173.5 to 176.5	White Sand Stone & Coal with shale band	150	12	73	1.5	1.00	2.22	1.98	28.84	3.01	47.80
7	Upper Roof of 5th seam	173.5 to 176.5	White Sand Stone & Coal with shale band	150	12	73	2.5	1.00	2.22	1.98	28.84	3.01	47.80
8	Main Floor after 4th seam	157 to 162	Sandy Shale & White Sand Stone	150	8	85	2.5	0.82	2.21	1.81	28.35	2.75	47.32
9	Main Floor after 4th seam	157 to 162	Sandy Shale & White Sand Stone	150	8	85	3.5	0.82	2.21	1.81	28.35	2.75	47.32
10	Main Floor after 4th seam	157 to 162	Sandy Shale & White Sand Stone	150	8	85	4.5	0.82	2.21	1.81	28.35	2.75	47.32
11	Main Floor after 4th seam	157 to 162	Sandy Shale & White Sand Stone	150	8	85	5.5	0.82	2.21	1.81	28.35	2.75	47.32
12	Main Floor after 4th seam	157 to 162	Sandy Shale & White Sand Stone	150	8	85	1.5	0.82	2.21	1.81	28.35	2.75	47.32
13	Immediate Roof of 5th seam	175.9 to 178.9	White Sand Stone	150	12	73	2.5	1.00	2.29	3.14	37.08	6.18	52.36
14	Immediate Roof of 5th seam	175.9 to 178.9	White Sand Stone	150	12	73	1.5	1.00	2.29	3.14	37.08	6.18	52.36
15	Immediate Roof of 5th seam	175.9 to 178.9	White Sand Stone	150	12	73	4.5	1.00	2.29	3.14	37.08	6.18	52.36
16	Immediate Roof of 5th seam	175.9 to 178.9	White Sand Stone	150	12	73	3.5	1.00	2.29	3.14	37.08	6.18	52.36

Table 11. Exploratory borehole data near the blast hole drilling

Investigation with 8.0 kg weight on bit during drilling was also carried out on Blast hole-1 having white sandstone with compressive strength of 36.49 MPa and Blast hole-12 containing sandy shale and white sandstone with compressive strength of 28.35 MPa. From the Fig. 16 it is observed that for the first 45.0 cm depth of drilling, the difference in sound level for Blast hole -1 and Blast hole-12 is as much as 6.7 dB. By neglecting the first 45.0 cm depth, it is observed that for increase in compressive strength by 8.14 MPa (UCS of Blast hole–1 and Blast hole–12), L_{eq} level increases up to 4.0 dB.

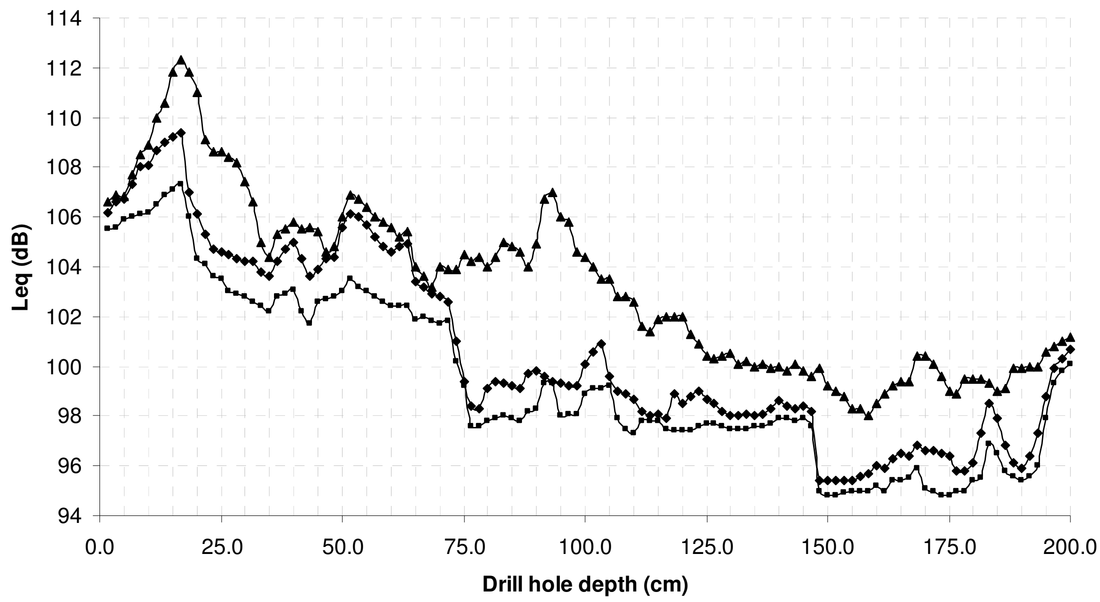

Fig. 17. L_{eq} vs drill hole depth with 12.0 kg weight on drill bit: ♦ Blast hole–2 (UCS 30.61 MPa); ■ Blast hole – 6 (UCS 28.84 MPa); ▲ Blast hole–14 (UCS 37.08 MPa).

Fig. 17 shows results of investigation with 12.0 kg weight on bit during drilling. In this case, Blast hole-2 was shale with white sandstone of compressive strength 30.61 MPa, Blast hole-14 was white sandstone of compressive strength 37.08 MPa whereas Blast hole-6 was white sandstone and coal with shale band of compressive strength 28.84 MPa.

It is observed that for the first 45.0 cm depth of drilling, the increase in sound level for Blast hole-2 compared to that of Blast hole-6 is as much as 2.2 dB. Similarly, the increase in sound level for Blast hole-14 compared to that of Blast hole-2 is as much as 4.9 dB. In addition, the sound level of Blast hole-14 is up to 6.7 dB higher than that of Blast hole-6. By neglecting the first 45.0 cm depth, it is observed that for increase in compressive strength by 1.77 MPa (UCS of Blast hole–2 and Blast hole–6), L_{eq} level increases up to 2.8 dB. For increase in compressive strength by 8.24 MPa (UCS of Blast hole–14 and Blast hole–6) L_{eq} level increases up to 8.0 dB. Similarly, for increase in compressive strength by 6.47 MPa (UCS of Blast hole–14 and Blast hole–2) L_{eq} level increases up to 7.1 dB.

This clearly indicates that as the compressive strength increases, the L_{eq} level produced during drilling also increases. However, this increase in L_{eq} level also depends on the weight on the bit which is indirectly related to the compressor pressure used.

It is also observed that between depths of 75.0 cm to 125.0 cm and 150.0 cm to 175.0 cm, the L_{eq} levels measured at Blast hole-6 and Blast hole-2 were somewhat similar whereas Blast hole-14 had an increase in L_{eq} value of up to 8.0 dB for depths between 75.0 cm and 125.0 cm and up to 5.3 dB for depths between 150.0 cm and 175.0 cm. This is because of the coal

present in Blast hole-6 and Blast hole-2 between these depths which was confirmed on observing the coal dust flushing out of the drill holes at these depths.
Table 12 gives the equivalent A–weighted sound levels for Blast holes of different compressive strengths at different measurement distances..

UCS (MPa)	*Weight on a bit (kg)*	*L_{eq} (dB)*									
		Blast hole	*1.5 m*	*Blast hole*	*2.5 m*	*Blast hole*	*3.5 m*	*Blast hole*	*4.5 m*	*Blast hole*	*5.5 m*
36.49	8.0	1	102.5	-	-	-	-	-	-	-	-
28.35	8.0	12	98.6	8	96.2	9	95.4	10	94.3	-	-
30.61	12.0	2	101.5	3	98.9	-	-	-	-	-	-
28.84	12.0	6	99.3	7	97.6	5	95.9	4	94.8	11	93.7
37.08	12.0	14	103.2	13	100.9	16	99.6	15	98.5	-	-

Table 12. Comparison of A-weighted equivalent sound level (L_{eq}) for Blast holes of different UCS at different measurement distances for first 2 minutes of drilling.

It was observed that as the measurement distance increases, the equivalent A–weighted sound level decreases. For example, 1.0 meter increase in distance from 1.5 m to 2.5 m, for UCS of 30.61 MPa (Blast hole–2 and Blast hole–3), the sound level decreased by 2.6 dB. Similar results were obtained at strata of different compressive strengths (Blast hole 6 and Blast hole 7, Blast hole 12 and Blast hole 8, Blast hole 14 and Blast hole 13).

3.4 Results of investigation using one-third-octave band analyzer

3.4.1 Comparison of drilling noise with machine noise

The A–weighted sound level spectrum at the measurement location with 8.0 kg weight on bit for Blast hole-1, Blast hole-12 and machine noise is shown in Fig. 18. It is seen that the maximum sound level at measurement location for Blast hole-1 is 96.4 dB, Blast hole-12 is 92.9 dB with nominal one–third–octave midband frequency of 63 Hz.
Similarly, A–weighted sound level at the measurement location with 12.0 kg weight on bit for Blast hole-2, Blast hole-6 and Blast hole-14 is shown in Fig. 19. It is seen that the maximum sound level at measurement location for Blast hole-2 is 100.3 dB, Blast hole-6 is 99.8 dB and Blast hole-14 is 104.1 dB with the nominal one–third–octave midband frequency from 25 Hz to 20 kHz.
In both the cases, the increase in sound level with midband frequencies above 50 Hz is more than 10.0 dB during drilling relative to that of machine noise without drilling. Therefore, the sound level in the frequency range of 63 Hz to 20 kHz, during drilling is unlikely to be affected by the background noise due to the compressor. However, the sound level produced during drilling may be affected due to machine noise with nominal midband frequencies from 25 Hz to 50 Hz as the difference in sound level in this range of frequency is below 10.0 dB.
From Fig. 18, it is seen that from 25 Hz to 50 Hz, the increase in sound level for Blast hole-1 relative to that of machine noise is from 6.7 dB to 9.6 dB and that of Blast hole-12 relative to that of machine noise is from 3.9 dB to 7.4 dB. Similarly, from Fig. 19 it is seen that from 25 Hz to 50 Hz, the increase in sound level, for Blast hole-2 relative to that of machine noise is from 2.7 dB to 8.4 dB, for Blast hole-6 relative to that of machine noise is from 1.2 dB to

7.0 dB and for Blast hole-14 relative to that of machine noise is from 5.3 dB to 9.4 dB. This shows that drilling operation has increased the sound level with midband frequencies from 25 Hz to 50 Hz. The increase in sound level in this frequency range (25 Hz – 50 Hz) may be due to impact between the drill bit and the rock.

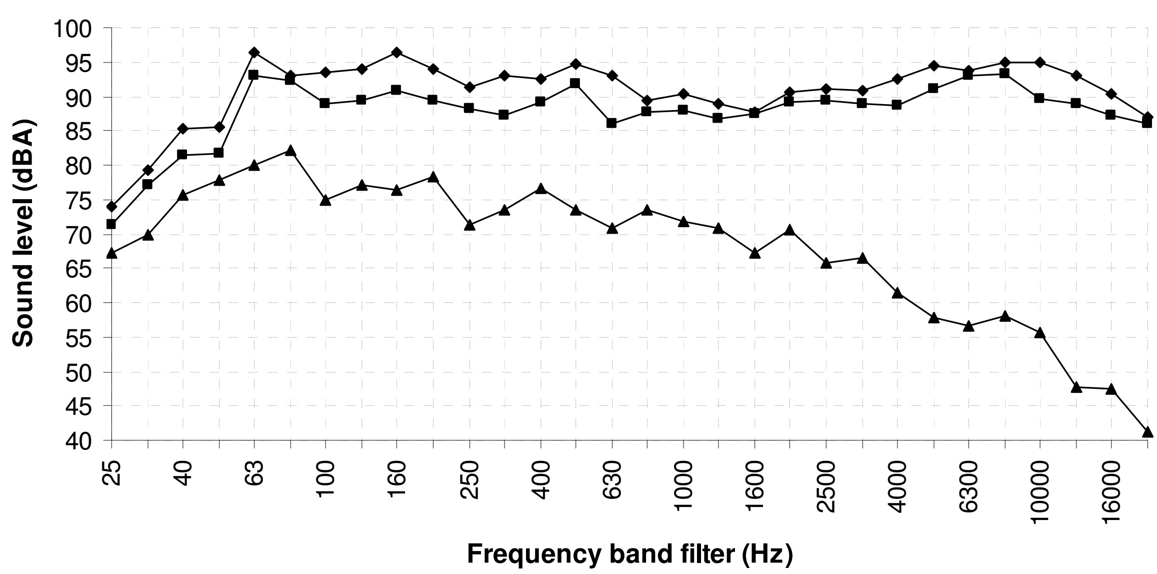

Fig. 18. Sound level vs nominal one-third-octave midband frequency with 8.0 kg weight on drill bit: ♦ Blast hole–1 (UCS 36.49 MPa); ■ Blast hole–12 (UCS 28.35 MPa); ▲ Machine noise (without drilling).

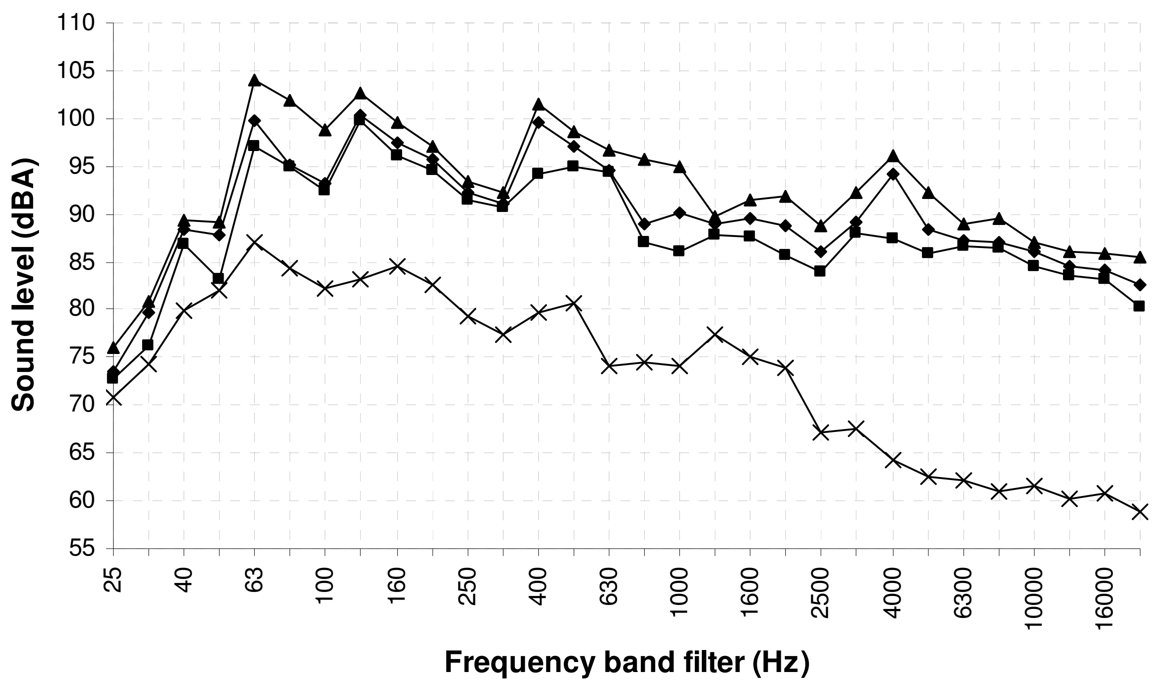

Fig. 19. Sound level vs nominal one-third-octave midband frequency with 12.0 kg weight on drill bit: ♦ Blast hole–2 (UCS 30.61 MPa); ■ Blast hole–6 (UCS 28.84 MPa); ▲ Blast hole–14 (UCS 37.08 MPa); × Machine noise (without drilling).

From Fig. 18, the increase in sound level for Blast hole-1 relative to that of machine noise with midband frequencies from 63 Hz to 2 kHz is from 10.8 dB to 22.1 dB and that of Blast hole-12 relative to that of machine noise is from 10.2 dB to 20.3 dB. Similarly from Fig. 19, the increase in sound level for Blast hole-2 relative to that of machine noise with midband frequencies from 63 Hz to 2 kHz is from 10.9 dB to 20.4 dB, for Blast hole-6 relative to that of machine noise is from 10.1 dB to 20.2 dB and for Blast hole-14 relative to that of machine noise is from 14.4 dB to 22.6 dB.

Also from Fig. 18, it can be observed that there is a significant increase in sound level of the order of 24.3 dB to 45.7 dB from 2.5 kHz to 20 kHz for Blast hole-1 relative to that of machine noise and 22.5 dB to 44.8 dB for Blast hole-12 relative to that of machine noise. Similarly, from Fig. 19, within frequency range of 2.5kHz to 20 kHz, the increase in sound level relative to machine noise for Blast hole-2 is from 18.9 dB 29.9 dB, for Blast hole-6 relative to that of machine noise is from 16.8 dB to 25.5 dB and for Blast hole-14 relative to that of machine noise is from 21.5 dB to 31.9 dB. This increase in sound level is due to resonance of the steel parts of the drill steel due to rock drilling.

3.4.2 Comparison of drilling noise with rock properties

With 8.0 kg weight on bit, the increase in sound level of Blast hole-1 (UCS of 36.49 MPa) compared to that of Blast hole-12 (UCS of 28.35 MPa), with midband frequencies from 25 Hz to 50 Hz, was of the order of 2.0 dB to 3.8 dB. The increase in sound level, with midband frequencies from 63 Hz to 2 kHz, was of the order of 0.3 dB to 6.9 dB. The increase in sound level, with midband frequencies from 2.5 kHz to 20 kHz, was of the order of 0.8 dB to 5.2 dB.

With 12 kg weight on bit, the increase in sound level of Blast hole-14 (UCS of 37.08 MPa) compared to that of Blast hole-2 (UCS of 30.61 MPa), with midband frequencies from 25 Hz to 50 Hz, was of the order of 1.0 dB to 2.6 dB. The increase in sound level, with midband frequencies from 63 Hz to 2 kHz, was of the order of 0.8 dB to 6.9 dB whereas the increase in sound level, with midband frequencies from 2.5 kHz to 20 kHz, was of the order of 1.0 dB to 3.8 dB. The increase in sound level of Blast hole-14 (UCS of 37.08 MPa) compared to Blast hole-6 (UCS of 28.84 MPa), with midband frequencies from 25 Hz to 50 Hz, was of the order of 2.4 dB to 6.0 dB. The increase in sound level, with midband frequencies from 63 Hz to 2 kHz, was of the order of 1.5 dB to 8.9 dB whereas the increase in sound level with midband frequencies from 2.5 kHz to 20 kHz, was of the order of 2.4 dB to 8.7 dB. The increase in sound level for Blast hole-2 (UCS of 30.61 MPa) compared to Blast hole-6 (UCS of 28.84 MPa), with midband frequencies from 25 Hz to 50 Hz, was of the order of 0.7 dB to 4.7 dB. The increase in sound level, with midband frequencies from 63 Hz to 2 kHz, was of the order of 0.2 dB to 5.3 dB whereas the increase in sound level, with midband frequencies from 2.5 kHz to 20 kHz, was of the order of 0.7 dB to 6.7 dB.

4. Conclusions

The laboratory study using portable pneumatic drilling equipment indicated that the sound level near the drill rod is relatively higher than that of the exhaust, the drill bit and the operator's position for all the rock samples tested. Both the thrust and air pressure were found to have a significant effect on the sound level produced by pneumatic drill at all the measurement locations i.e., at operator's position, exhaust, drill rod and the drill bit.

The laboratory study using CNC machine was carried out to evaluate the empirical relation between various rock properties and sound level produced during drilling considering the effects of drill bit diameter, drill bit speed and penetration rate. The empirical relationship developed is not aimed at replacing the ISRM suggested testing methods, but rather as a quick and easy method to estimate the physico-mechanical properties of rock. The results of this study could be used to predict the physico-mechancial properties of igneous rocks.

In the field investigation, results of frequency analyser shows that the sound level in the frequency range of 63 Hz to 20 kHz, during drilling is unlikely to be affected by the background noise because above 50 Hz the sound level produced is more than 10 dB during drilling relative to that of machine noise without drilling. However, the sound level produced during drilling maybe affected due to machine noise with nominal midband frequencies from 25 Hz to 50 Hz as the difference in sound level in this range of frequency is below 10 dB.

Results from both laboratory and filed investigations show that there is a possibility to establish relationship between rock properties and sound level produced during drilling. The present investigations lead to further research in this direction.

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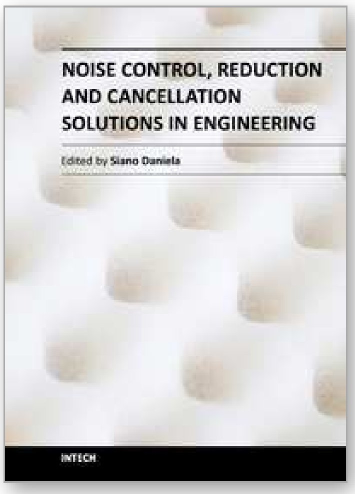

Noise Control, Reduction and Cancellation Solutions in Engineering
Edited by Dr Daniela Siano

ISBN 978-953-307-918-9
Hard cover, 298 pages
Publisher InTech
Published online 02, March, 2012
Published in print edition March, 2012

Noise has various effects on comfort, performance, and human health. For this reason, noise control plays an increasingly central role in the development of modern industrial and engineering applications. Nowadays, the noise control problem excites and attracts the attention of a great number of scientists in different disciplines. Indeed, noise control has a wide variety of applications in manufacturing, industrial operations, and consumer products. The main purpose of this book, organized in 13 chapters, is to present a comprehensive overview of recent advances in noise control and its applications in different research fields. The authors provide a range of practical applications of current and past noise control strategies in different real engineering problems. It is well addressed to researchers and engineers who have specific knowledge in acoustic problems. I would like to thank all the authors who accepted my invitation and agreed to share their work and experiences.

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