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Investigating an innovative model for dimensional sedimentary rock characterization using acoustic frequency analysis during drilling

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Abstract
Determining geomechanical characteristics of rocks plays a significant role in all consequent designing stages of geosciences. On the other hand, drilling is one of the considerable operations in the primary phases of extracting rocks. The drilling process produces acoustic signals as a by-product of drilling. Hence, one possible way for predicting geomechanical properties of rocks is by employing acoustic signal frequencies, which are produced during drilling. This process helps geoengineers determine rock characteristics in a short time with low-cost and satisfying precision. This research tries to develop some novel computational relations between geomechanical characteristics of sedimentary rocks and the produced dominant acoustic frequencies by implementing Fast Fourier Transform (FFT). For this purpose, a novel rotary drilling machine was developed by researchers. In order to introduce a reliable model, 10 diverse sedimentary rock samples from various sedimentary basins of Iran were gathered in a wide range of geomechanical features, and all tests were carried out on them. The results of this research could be used for sedimentary basins' characterization. The results show that there are reliable mathematical relations between various characteristics of sedimentary rocks (Uniaxial Compressive Strength (UCS), Tensile Strength (TS), porosity and hardness) and diverse dominant frequencies.

Keywords
Dimensional sedimentary rocks; geomechanical features; acoustic; Fast Fourier Transform (FFT)

1. Introduction

The determination of physical and mechanical properties of rocks is one of the construction engineers' main concerns in different downstream designations. There are several considerable complexities about determining the geomechanical properties of rocks. One of the major problems with this issue is time-consuming, which is not always complete and satisfactorily solved using conventional approaches. The other problem is the cost of this operation, which depends on the project location, regional facilities, the availability of accredited laboratories and so on. Another important factor in defining these features is accuracy, which is entirely dependent on the designing level and type. One major disadvantage of conventional methods for determining geomechanical features is the destructive nature of those tests.

Rock drilling is a fundamental process in construction-related projects. Generally, the drilling process always produces acoustic signals as a by-product. This sound is generated as a result of the collision of the drill bit and the rock mass, regardless of the type of drill bit or drilling materials. During the drilling process, determinacy of the rock type and its geomechanical characteristics has a particular importance. Drilling has a direct relationship with the type and geomechanical properties of the intact rock. One possible way for achieving the physical and mechanical features of rocks is analyzing the sound generated during drilling.

Acoustic emission studies in rocks began by Obert in 1941 and Obert and Duvall in 1942 to predict rock burst in mines **(Obert, 1941; Obert & Duvall, 1942)**. After these studies, researchers focused on changes of acoustic wave amplitude over a frequency band with increasing tension **(Byerlee, 1978; Hardy, 1972; Knill, Franklin, & Malone, 1968; Marceau & Moji, 1973)**. In 1990, after studying UCS test results in thousands of core samples and comparing them with geophysical logs in Basin Bowen, McNally presented an exponential relationship between UCS and sonic logs **(McNally, 1990)**. In 1996, Zang et al. recorded and analyzed time–point and Acoustic Emission (AE) curves **(Zang, Wagner, & Dresen, 1996)**. In 1997, Hsu et al. considered the identification of formations under pressure by using sonic tools during drilling **(Hsu, Gao, Sorooshian, & Gupta, 1997)**. By continuing the McNally method in 1998, local conditions were involved in UCS estimation from sonic logging. For this purpose, local formulas were presented in strong and weak layers of mines in Germany and Greece **(Ward, 1998)**.

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After 2000, acoustic studies in rocks experienced a new phase. The basis of these studies was the sound simultaneously produced during drilling. Researchers tried to establish a logical relation between the physical-mechanical features of rocks and the generated sound. In 2001, the identification of rocks during drilling was investigated by Zborovjan using audio signal analysis. In this study, it was proved that acoustic frequencies caused by drilling are between 5,000 and 8,000 Hz and fewer spectrum signals are emitted with the engine and cooling fluid drainage **(M Zborovjan, 2001)**. In 2002, Hatherly offered another method in order to estimate the UCS of elastic rocks using geophysical log data **(Hatherly, 2002**). In 2003, Zborovjan et al. came to the conclusion that acoustic signal analysis can be used for the management of the drilling process and classify rocks **(Martin Zborovjan, Lesso, & Dorcak, 2003)**. A novel model was presented by Benavente et al. in 2006 for evaluating the strength of two types of rocks by using signal processing procedures **(Benavente, Martınez-Martınez, Jáuregui, Rodrıguez, & del Cura, 2006)**. In 2006, Williams and Hagan discussed variations of acoustic signals generated during the cutting of stones by changing cutting conditions. It was found that changes in stone cutting conditions have measurable effects on acoustic signal emissions **(Williams & Hagan, 2006)**. In 2006, Miklusova et al. developed a laboratory device for simulating the disintegration of rocks during rotary drilling with a small diameter **(Miklusova, Usalova, Ivanicova, & Krepelka, 2006)**. In 2007, Kostur et al. discussed the possibility of optimal drilling rock by monitoring the acoustic signals. As a result of this study, it was found that the frequency of the representative signal sample depends on the rock type **(Kostur & Futo, 2007)**. In a laboratory study in 2007, Vardhan and Murthy checked out the relationship between jackhammer sound level and the compressive strength and abrasion of drilled rock **(Vardhan & Murthy, 2007)**. In 2007, the possibility of extracting drill bit features using acoustic data was examined by Roy and Adhikari **(Roy & Adhikari, 2007)**. In 2008, Gradl et al. claimed that drill bit properties can be determined by using the acoustic data **(Gradl, Eustes, & Thonhauser, 2008)**. In 2009, an attempt was made by Vardhan et al. to investigate the effect of sound levels in the characterization of rocks. They came to the conclusion that sound level produced during drilling will change with variations of rock properties **(Vardhan, Adhikari, & Raj, 2009)**. In 2010,, Leššo et al. examined vector quantization method in order to clear monitoring of rotary drilling using vibro-acoustic signals **(Leššo, Flegner, & Špak, 2010)**. In their studies in 2010, Kumar et al. attempted to predict the geomechanical properties of rocks by monitoring the sound level **(Kumar, Vardhan, & Govindaraj, 2010)**. In 2011, in the rest of their investigation, Kumar et al. predicted the physical and mechanical properties of metamorphic rocks using regression models **(Kumar, Vardhan, & Govindaraj, 2011b)**. By continuing their studies in 2011, these researchers tried to prognosticate UCS, TS and porosity of sedimentary rocks using an equivalent sound level, drill bit diameter, rotational speed and penetration rate **(Kumar, Vardhan, & Govindaraj, 2011a)**. In 2013, these researchers attempted to predict the sound level and drilling penetration rate using uniaxial compressive strength, air pressure and thrust force of a drilling machine by using artificial neural networks **(Kumar, Vardhan, Govindaraj, & Saraswathi, 2013)**. In 2012, Gradl et al. measured the derived frequencies from drilling using a microphone and a geophone. They analyzed the relation of designation parameters of a drill bit through seismic and acoustic properties of emitted frequencies **(Gradl, Eustes, & Thonhauser, 2012)**. In 2015, Kivade et al. predicted the physical and mechanical properties of rock such as: UCS, Schmidt rebound number, dry density, P-wave velocity, TS, modulus of elasticity and porosity, using multiple regression, MLP and RBF models **(Kivade, Murthy, & Vardhan, 2015)**. In 2016, in a consequent stage of implementing Artificial Intelligence (AI) models in geomechanical features of rock samples, Briševac and Kujundžić implemented multiple regression and ANN (RBF and MLP) models for predicting tensile strength of rocks in saturated conditions **(Briševac & Kujundžić, 2016)**. Through a comprehensive study in 2014, Flegner et al. examined the relationship between vibro-acoustic signals and the nature of the drilling process **(Flegner, Kačur, Durdán, Leššo, & Laciak, 2014)**.

Previous studies have used CNC machines for the drilling operation. These facilities are only available in fully-equipped research centers. Using these devices, the cost of studies significantly increases and research becomes purely laboratory work in a particular time and place. This limitation reduces the validity of the study.

In this study, using a novel rotary drilling machine, which was designed and constructed by the researchers, drilling tests have been executed. This low-cost device with adjustable thrust force, rotational speed, material and diameter of the drill bit and audio recording capability, dramatically reduces the test costs. This machine makes it possible to extend the results of the study to different places.

Previous studies indicate that, generally, there are logical relationships between different rocks' features and the sound level of the drilling operation. In a majority of these studies, the sound level of drilling is measured and further analysis on acoustic signals have been avoided. As it has been noted in previous studies, it is necessary to use other analyzing methods such as Fast Fourier Transform (FFT) for transferring data to the frequency domain **(Vardhan & Bayar, 2013)**.

In this study, for the first time, it has been tried to investigate a non-destructive testing model for providing mathematical relationships between the geomechanical properties of rocks and acoustic signals of the drilling

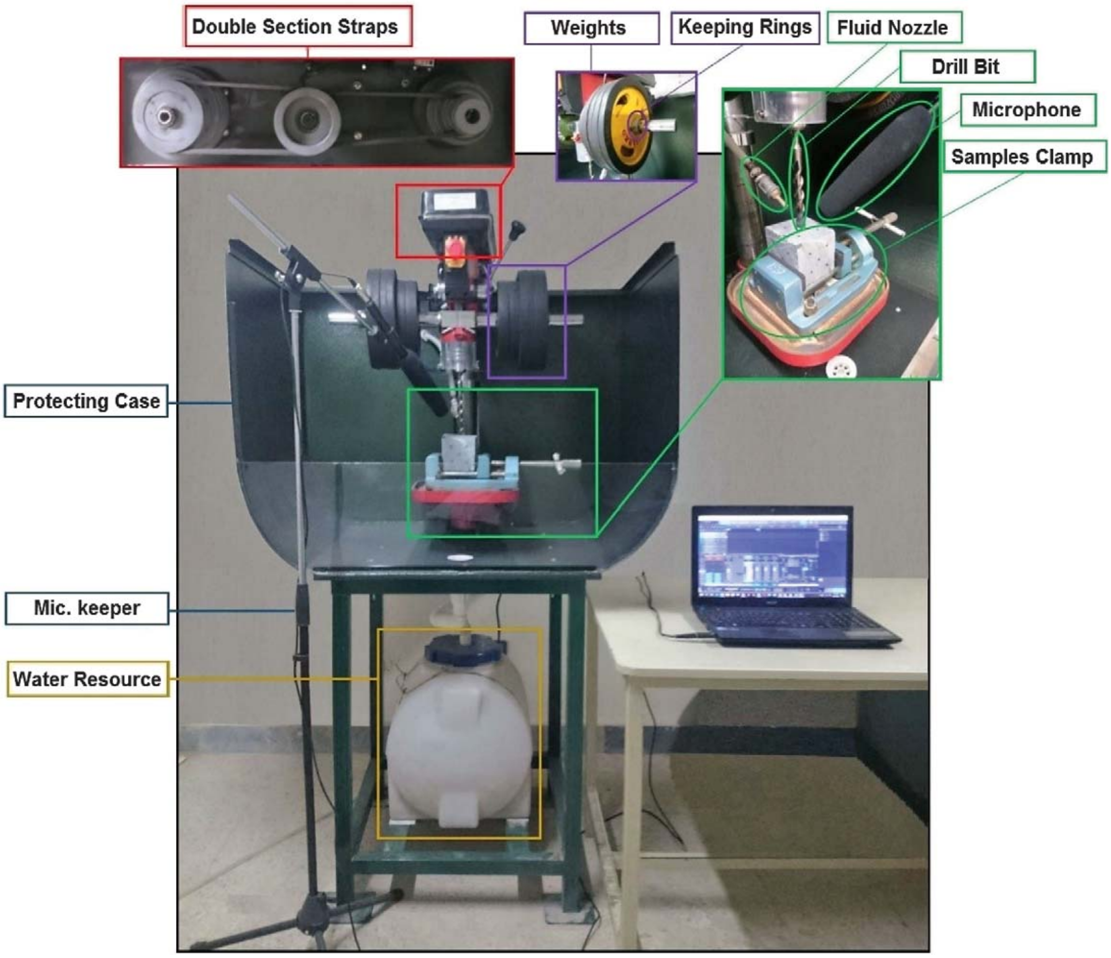

Figure 1: Developed rotary drilling device

process. For achieving this goal, the drilling regime (thrust force behind the drill bit, rotational speed, the material and diameter of the drill bit, sound recording system) should be completely controllable. This purpose was achieved by manufacturing the presented novel rotary drilling machine.

2. Materials and methods

2.1. Developed Rotary Drilling Device

The construction of this device is based on fixed rotary drilling equipment. In order to create the appropriate conditions, affecting the variables of the drilling regime such as thrust force behind the drill bit, drill bit rotational speed, sound recording, cooling fluid flow, the diameter and material of the drill bit should be controllable. The constructed device includes different components that every section controls one of the influencing factors (see **Figure 1**).

The device contains the following mechanisms:

A. **Electrical motor**: The task of this part is rotating the drill bit with different speeds. The rotational speed can be adjusted by changing the position of the double section straps on the upper part of the device. This speed is customizable between 210 RPM and 2580 RPM.

B. **Thrust force suppliers**: In order to generate equal conditions for all drilling tests, thrust force should be fixed behind the drill bit. For this purpose, two symmetrical steel arms are connected just above the drill bit, which must bear the installed weights. This symmetry leads to apply a zero torque to the drill bit. For kipping weights, fixed and stable at the end of the arms, two steel bolt rings were used. These rings decrease the sound and vibration produced by the collision of the weights together. For further reduction of these unwanted phenomena, a plastic cover is used in the outer surroundings of the weights. Similarly, in order to diminish the emitted sound induced by the collision of the weights and steel arms, plastic coverage is implemented in the inner surroundings of the weights.

C. **Holder pillar of the engine**: electrical motor and weights are installed on a holder pillar. Furthermore, this pillar controls the vertical movement of the drill bit with considerable accuracy.

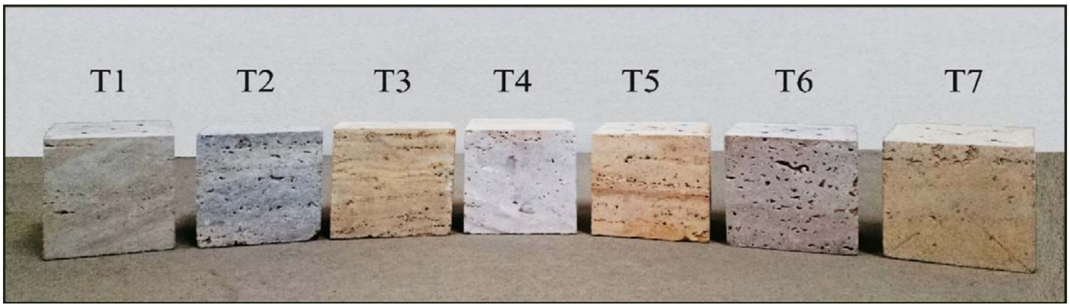

Figure 2: Different sedimentary rocks samples

D. **Samples holding clamp**: This part plays the role of adjusting the height and position of the rock samples in various directions and keeps rock samples fixed and motionless during the drilling process.
E. **Drilling fluid controller**: this section streams fluid onto the drill bit during drilling. The presence of water in the drilling operation leads to a reduction of dust particles, protects the drill bit from overheating and reduces noise.
F. **Computer**: the PC records acoustic signals, stores information and processes recorded signals.
G. **Protective case**: This part prevents water from splashing to the surrounding area.
H. **Water reservoir**: Streamed water during the drilling process transfers to a water reservoir in the bottom part of the device and discharges using an embedded valve.
I. **Microphone**: A focal microphone is responsible for recording acoustic signals during drilling. By connecting the microphone to the computer, this helps to record the desired audio signal. An AR-321 focal microphone with remarkable sensitivity is used for this experiment. For achieving acceptable and reliable results, this part should be selected carefully. The employed microphone should focus sound recording on the collision spot of the drill bit and samples. The microphone should be able to record the sound of drilling with the highest quality and minimal disruptive noises.

2.2. *Dimensional sedimentary rocks (Travertine) Samples*

10 different sedimentary rock samples were selected in a wide range of geomechanical and physical properties. As presented in the last section, this research attempts to find mathematical relations for calculating geomechanical features of rocks by means of extracted dominant frequencies from recorded drilling operations. With the intention of this purpose, physical, mechanical, and drilling tests should be executed for all gathered samples. 7 types (see **Figure 2**) of samples are used for model development and another 3 are employed for validating the achieved results. **Table 1** illustrates all the physical and mechanical specifications of these 7 samples.

Table 1. Physical-mechanical characteristics of sedimentary (Travertine) samples

Code	UCS (Mpa)	TS (MPa)	Pro (%)	H (SRN)
T1	47.84	6.31	2.75	52.69
T2	35.31	5.73	4.66	51.38
T3	33.98	5.49	5.80	43.67
T4	30.70	3.73	5.33	48.20
T5	33.50	4.51	5.81	30.71
T6	30.20	4.57	3.56	45.73
T7	28.94	5.26	7.31	18.60

Table 2. Implemented standards for geomechanical tests

Test	Standard
Uniaxial compressive strength (UCS)	ASTM C170
Brazilian test/indirect tensile strength (TS)	ISRM/ASTM D3967
Hardness/Schmidt Rebound Number (SRN)	ISRM
Physical Tests	ISRM

For setting a fixed condition in all the drilling tests, a standard dimension is specified for drilling test samples by researchers. This standard dimension is defined based on the drilling device capacity, the dimensions of the keeping clamp, the diameter of the drilling and the penetration depth. After accurate exploration 9×9×9 cm^3 cubic dimension was selected for samples of the drilling tests. Geomechanical features of sedimentary rocks are determined to implement standards, which are mentioned in **Table 2**.

3. Implementation of method

In the first step, 9×9×9 cm^3 cubic travertine samples should be primed for drilling tests. Samples should be fixed on a clamp in such a way that the orientation of the drill bit must be set in a defined point. The desired rotational speed should be established before beginning the

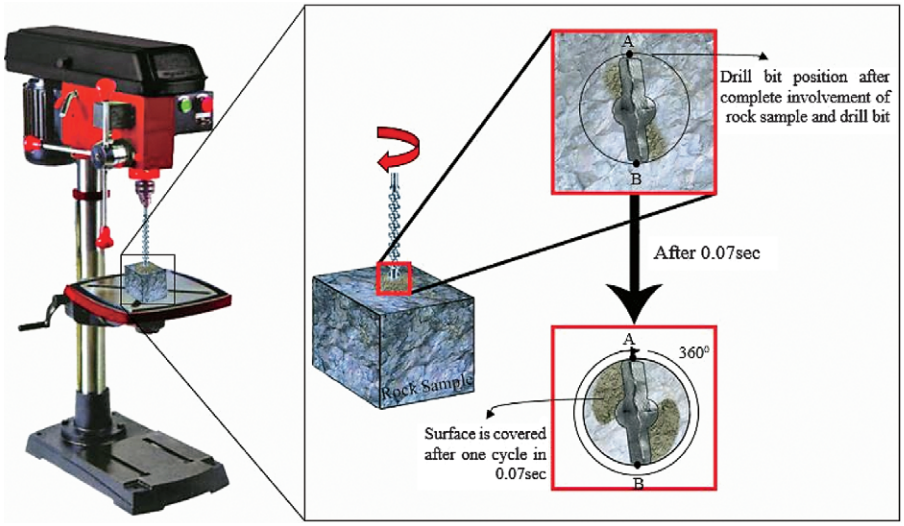

Figure 3: Schematic of the required time for a complete rotation of the drill bit

drilling process. For achieving comparable outputs, the rotational speed of the drill bit is fixed at 830 RPM by employing the double-part straps on top of the device. Additionally, the vertical force behind the drill bit should be fixed at a favorable constant level during all drilling tests for all rock samples. The installed weights on symmetrical steel arms provide this goal for the system. 400 N force is applied to the system vertically by dividing itself equally into both sides of the arms (each side equals to 200 N). The selected drill bit is a diamond rotary one, 1.8 cm in diameter. As it stands, all the affecting parameters (vertical force, rotational speed, material, and diameter of the drill bit) on the drilling operation are fixed on a constant condition through all the drilling tests.

The drilling head of the bit has a V shape. There is a 2-3 mm vertical distance between the lowest point of the drill bit and the level of the drill bit's outer edges. After starting the drilling process, this distance should be penetrated for complete engagement of the drill bit and the rock sample. All the frequencies should be recorded after the entire engagement of the drill bit and the rock sample. In the following phase, the location of the focal microphone should be determined in a way that the longitudinal orientation of the microphone crosses the engagement point (of the rock sample and the drill bit). In this position, the focal microphone is concentrated on drilling frequencies and eliminates recording the undesirable environment audios (machine vibration noises, cooling fluid splashing, surrounding sound, etc.). This capability of the focal microphone helps to pre-filter unwanted frequencies. A soundproof cable connects the focal microphone and the computer. The audio of all the drilling tests was recorded by a sampling rate of 48000.

The embedded water valve behind the drill bit provides cooling water for the drilling operation. In addition, the added water helps to reduce drilling dust and the coarse sound of this operation. The cooling water, the drill bit, and the penetration point of the sample reach each other in the collision point of the rock and the bit.

The drilling operation starts by pressing the start button. After that, the penetration distance reaches to complete the engagement distance, the system starts to record the generated acoustic signals. Acoustic signals record for 20 s, because former results indicate that audio samples more than 25 s do not help to get better outputs (Zborovjan, 2001; Zborovjan et al., 2003). After recording the necessary audio, the rock sample is substituted with the next one. All the mentioned steps repeat for the

Table 3. Five dominant frequencies Travertine samples

Code	F1	F2	F3	F4	F5
T1	5531.250	5718.750	5893.750	6234.375	6562.500
T2	5296.875	5484.375	5671.875	5906.250	6046.875
T3	5296.875	5484.375	5625.000	5812.500	6234.375
T4	4593.750	5343.750	5671.875	6093.750	6656.250
T5	5109.375	5343.750	5437.500	5625.000	5953.125
T6	5109.375	5343.750	5671.875	5906.250	6140.625
T7	5109.375	5250.000	5343.000	5671.000	6843.750

Table 4. Detailed statistical features of models and t-test and f-test results

	Model	R	Predictor	F-test	Sig.	t-test	Sig.
UCS	Linear	0.954	F2	51.024	0.001	7.143	0.001
TS	Linear	0.934	F1	34.331	0.002	5.859	0.002
H	Linear	0.930	F3	32.054	0.002	5.662	0.002
Porosity	Linear	0.897	F3	20.699	0.006	-4.550	0.006

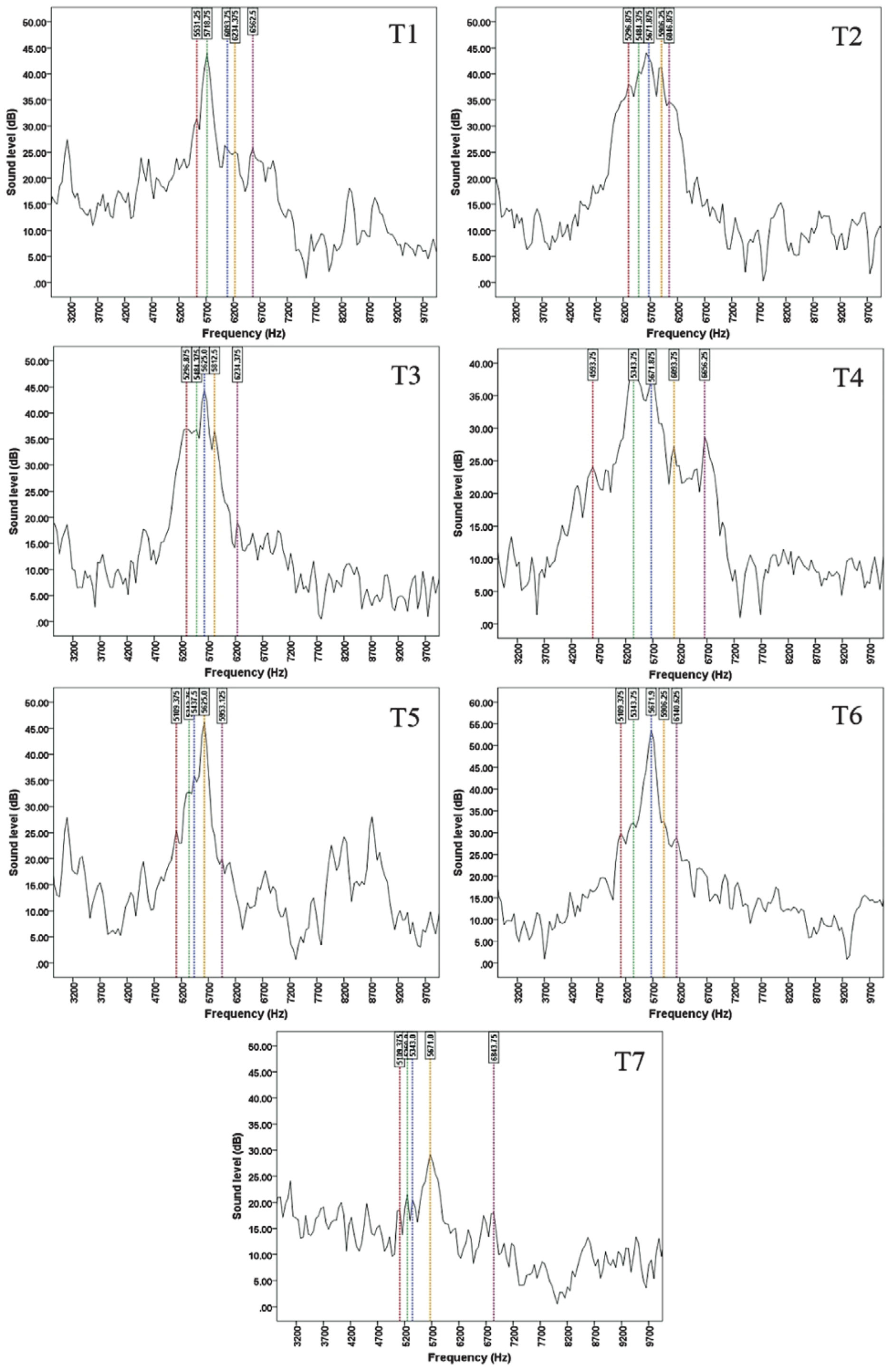

Figure 4: Five dominant frequencies in sedimentary (Travertine) samples

new sample. The reserved cooling fluid in the bottom reservoir discharges by releasing an embedded valve behind the reservoir. As mentioned, the rotational speed of drilling tests is fixed at 830 RPM. This means that there are 1660 engagements of rock and the drill bit every minute. It should be considered that one complete engagement (as a representative sample of all 20 s of recorded audio) is enough for signal analysis because using additional cycles applies extra undesirable frequencies to the system. As a result, it takes about 0.07 s for an entire rotation of the drill bit. **Figure 3** illustrates this fact clearly. This process is a kind of pre-filtering which prevents applying any unwanted frequencies and their disrupting harmonics to the system.

4. Results and Discussion

Drilling experiments are executed on seven different types of travertine with diverse geomechanical features. In the primary stage, the sound of the drilling process is recorded for 20 seconds. In the previous section, it is noted that 0.07 seconds representative cuts should be prepared for acoustic signal processing. In this time, the entire drilling surface of the rock is touched by the entire environment of the drill bit. The sampling rate of the recorded signals is 48000 Hz with a resolution of 32 bits. For providing a clear illustration of the recorded frequencies in the frequency domain, a linear spectrogram is extracted for divers drilling samples by the size of 4096 implementing the Hanning function as shown in **Figure 4**. In **Figure 4**, five dominant frequencies for different samples are determined regarding the sound level (dB) of each frequency. There are shown using colorful dotted lines. These five fundamental frequencies are representative indexes of rocks for eliciting geomechanical features. Drilling regime factors (rotational speed, vertical force, material, and diameter of the drill bit, cooling fluid volume) for all tests were constant for attaining comparable outcomes. Five fundamental frequencies are shown in **Table 3** for various samples.

Table 5. Measured values, obtained values from the prediction models and model error for UCS, TS, SRN and Porosity models (3 validation samples)

Code	T8	T9	T10
Measured UCS	29.32	34.14	28.74
Predicted UCS	27.86	33.35	29.69
UCS Model Error (%)	4.97	2.34	3.31
Measured TS	5.87	5.81	6.12
Predicted TS	6.09	6.09	5.95
TS Model Error (%)	3.81	4.88	2.73
Measured SRN	41.15	47.57	48.53
Predicted SRN	44.39	44.39	44.39
SRN Model Error (%)	7.85	6.70	8.55
Measured Porosity	2.81	2.72	2.72
Predicted Porosity	2.93	2.93	2.93
Porosity Model Error (%)	4.41	7.89	7.68

Finally, all mechanical and physical features of the sedimentary rock (Travertine) samples are evaluated based on the aforementioned method. The main purpose of this research is developing a logical correlation between dominant frequencies and the physical-mechanical properties of sedimentary rocks. The linear regression method is used for examining the verification and applicability of mathematical relations. **Equations (1)** to

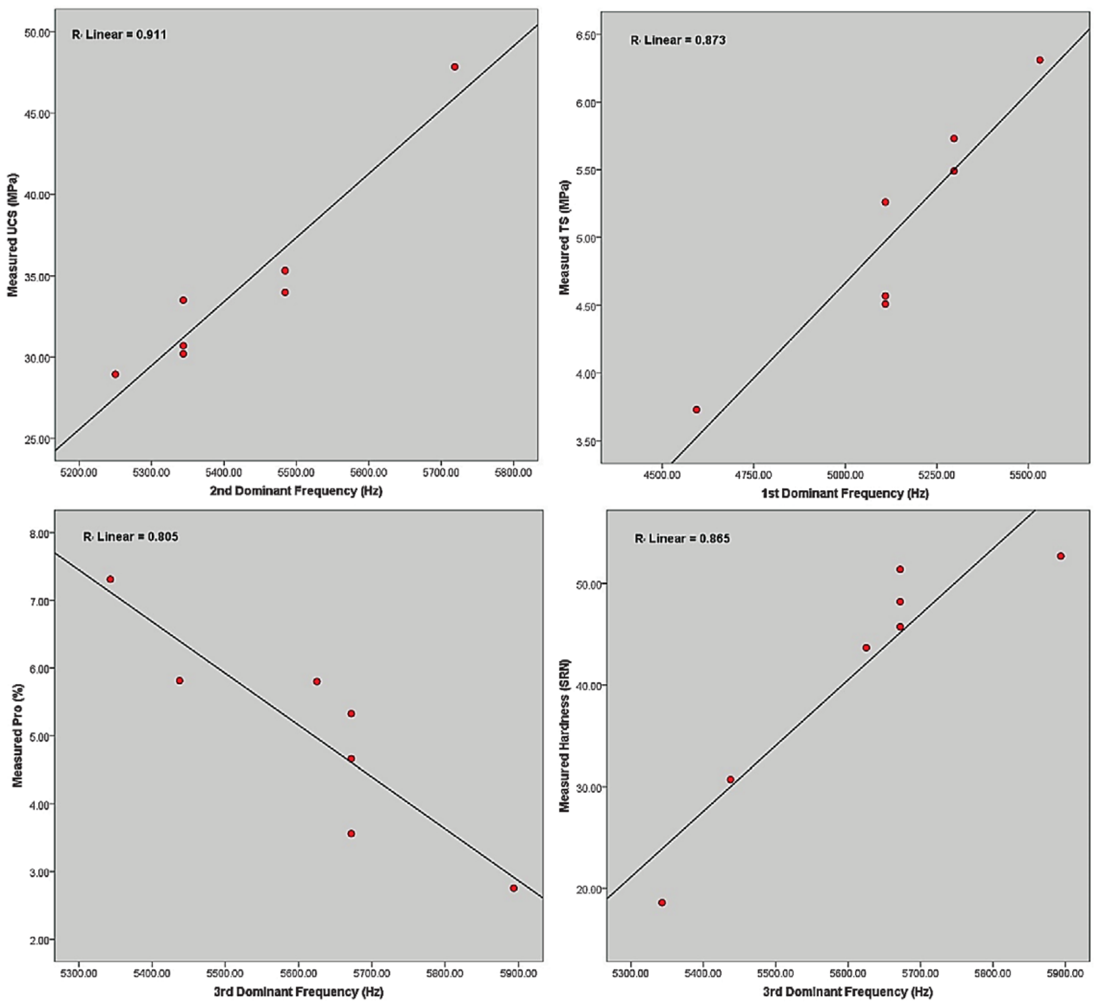

Figure 5: Linear regression model for UCS, TS, Porosity, and Hardness

(4) are suggested for predicting geomechanical properties of sedimentary (Travertine) rocks. These relations prognosticate uniaxial compressive strength (UCS), tensile strength (TS), porosity percentage, and Schmidt rebound number (SRN).

$$UCS = -178.716 + 0.039 \times F_2 \qquad R = 0.954 \qquad (1)$$

$$TS = -9.375 + 0.003 \times F_1 \qquad R = 0.934 \qquad (2)$$

$$Porosity = 47.932 - 0.008 \times F_3 \qquad R = 0.897 \qquad (3)$$

$$SRN = -321.293 + 0.065 \times F_3 \qquad R = 0.930 \qquad (4)$$

As observed, all the relations have adequate accuracy and a satisfying R. Detailed statistical features of **Equations (1), (2), (3)** and **(4)** and results of the t-test and f-test are presented in **Table 4**.

For validating the results of the presented model, three different Travertine samples are separated from seven modeling samples. The measured and evaluated (using presented linear models) values and predicting errors (percentage) are compared in **Table 5**. For clarifying of the accuracy of the models, the plots of predicting values against measured values are illustrated in **Figure 5**. Obviously, all the suggested models have acceptable and reliable results and related errors are less than 10%.

5. Conclusion

One of the sensitive phases in all the fields of geoengineering is drilling. For exploring this operation, a novel laboratory-scale rotary drilling machine was designed (with the capability of controlling all drilling regime factors and recording acoustic frequencies of drilling). This process generates audio signals as an undesirable by-product (noise pollution). On the other hand, determining the geomechanical features of rocks is one of the significant considerations of geoengineers. This research developed mathematical relations between the emitted drilling audio signals and the physical-mechanical characteristics of sedimentary rocks. For achieving this purpose, geomechanical and drilling tests were executed on 10 diverse travertine samples. Five dominant frequencies of drilling audio were extracted by FFT. All drilling tests were carried out by a novel rotary drilling machine, which was constructed by the researchers. All the factors of the drilling regime (vertical thrust force, rotational speed, drill bit diameter and its material, etc.) are manageable in this device and then all the results are comparable.

Finally, the results indicate that rock mechanical features of Travertine are predictable using dominant frequencies produced during the drilling operation. First, the dominant frequencies could be used as a predictor of tensile strength (TS). Uniaxial Compressive Strength (UCS) is prognosticated by implementing a second dominant frequency as a linear model. Porosity percentage and hardness of travertine have a respectively inverse and direct relation with third dominant frequencies. Statistical indexes show that the presented models are reliable and applicable for Travertine.

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SAŽETAK

Inovativni model za istraživanje i opisivanje obrađenih taložnih stijena analizom zvučnih (akustičnih) frekvencija dobivenih tijekom bušenja

Određivanje geomehaničkih svojstava stijena ima važnu ulogu u njihovim opisima i karakterizacijama u svim geoznanostima. Samo bušenje takvih stijena gotovo je obvezatna operacija koja se izvodi tijekom njihova ispitivanja i pridobivanja. Pri tome nastaju zvučni (akustični) valovi, kao rezultat uporabe različite opreme za bušenje. Upravo uporaba tih valova može pomoći kod određivanja geomehaničkih svojstava (pro)bušenih stijena. Takav postupak relativno je jeftin, a pruža zadovoljavajuću razlučivost ispitivanja. U radu je prikazan prilično nov pristup povezanoga računa geomehaničkih svojstva taložnih stijena i prevladavajućih zvučnih frekvencija, primjenom brze Fourierove transformacije. Također je razvijena izvorna, eksperimentalna rotacijska oprema za bušenje. Njome je obrađeno deset uzoraka prikupljenih u različitim taložnim bazenima Irana s različitim geomehaničkim svojstvima. Dobiveni su rezultati svojstava samih uzoraka, ali i prostora u kojima su prikupljeni. Zaključeno je kako postoje pouzdane matematičke veze između svojstava različitih taložnih stijena, opisanih varijablama jednoosne tlačne čvrstoće, vlačne čvrstoće, šupljikavosti i tvrdoće, te snimljenih zvučnih (akustičnih) frekvencija.

Ključne riječi
obrađene taložne stijene, geomehanička svojstva, zvučni valovi, brze Fourierove transformacije

Author contribution

Mojtaba Yari and **Raheb Bagherpour** shared contributions in the experimental and theoretical parts of the paper as well as laboratory works.