



# Monitoring and Studying Audible Sounds Inside Different Types of Soil and Great Expectations for its Future Applications

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**Abstract**—A majority of seismological studies are concerned with soil properties in low frequencies (1–10 Hz), but little is known about these properties in the audible sound domain (20–20,000 Hz). This is probably due to the high attenuation of the high frequencies within the soil, resulting in a minimal effect on buildings. For this study, 172 stations were recorded over different types of soils using variable types of P-wave and S-wave geophones to examine the variation of soil properties in the range of audible sound (20–3000 Hz). High resolution 32 bit spectrograms for the sounds recorded within every soil sample were analyzed. Moreover, a model for empty room was built in the subsurface to study changes in sound caused by the existence of large voids or cavities in the subsurface. The sound wave was able to differentiate between rigid, hard soil and softer, weaker soil. While high-strength rocks or soils tend to show sharp sound pitches (300–3000 Hz), weaker soils show lower sound pitches (20–100 Hz). The existence of subsurface voids or cavities tend to make sound pitches more regular, higher and sharper than those in the surrounding soils. This is most probably due to resonance of sound in closed places (e.g. a violin). Soil energy levels and how they change due to the soil's excitation were studied. Soil research in the field of audible sounds is considered an emerging field with several applications (e.g. geological hazards, water exploration, and oil exploration and so on). There is a need for special high-resolution equipment to be developed for the same. This equipment should be capable of recording wide range of sound frequencies preserved in the soil and directly producing high-resolution spectrograms.

**Keywords:** Spectrograms, audible sound, soil frequency, pitches, resonance of sound, microtremors, seismic frequencies, sound frequencies, soil voiceprint.

## 1. Introduction

Early studies employed seismic noises or the so-called “microtremors” in the frequency range of 1–10 Hz to study soil properties. In 1957, Kanai became the first scientist to introduce the technique of using microtremors or ambient seismic noises to determine soil response (soil amplification) to earthquake energy. After him, there were a lot of scientists who continued Kanai's work (Aki 1957, Kanai and Tanaka 1961; Kanai 1962; Nogoshi and Igarashi 1971; Kagami et al. 1982, 1986; Rogers et al. 1984; Celebi et al. 1987; Lermo et al. 1988; Nakamura 1989, 1997, 2000; Bour et al. 1998; Dimitrios et al. 2001; Mahajan et al. 2012; Harutoonian et al. 2012; Mahajan et al. 2012; Evangelia Bouranta et al. 2013; Adib et al. 2015; Ismail Akkaya 2015; Mohamad Ridwan et al. 2015; Yujing Jiang et al. 2016; Singh et al. 2017; Mohamed Gamal et al. 2019).

Scientists such as Mucciarelli (1998) excluded some sources, including winds or the sounds coming out of the asphalt layers (asphaltic waves), and considered them as non-favorable records that will result in an erroneous determination of soil response. Nakamura (1989) used microtremors in his study to provide a significant contribution to the literature related to the dynamic site properties such as period and amplitude. Such old microtremors or seismic noises are inaudible to the human ear but were effective in determining the soil response to earthquake energy (Horike 1985; Ishida et al. 1998; Miyakoshi et al. 1998; Scherbaum et al. 1999; Yamamoto 2000).

In fact, there is a significant amount of contradictions among scientists regarding the correct type of noise that can be useful in properly determining

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the soil response. When a few studies such as Field et al.'s (1990) employed calm microtremors coming from far distances for the purpose, other studies deemed it as being insufficient. Other studies used a large source of sound such as a helicopter to cause vibrations to excite the soil in order to get better results. However, both were right in the sense that both calm and excited soil must be studied in order to determine the overall effect on the soil. This overall effect will be presented in detail by this study.

Most studies have used microtremors (low amplitude oscillations 1–10 microns) in the frequency range of 1–10 Hz to identify the soil properties. The study of soil responses is very important in determining which buildings will be affected the most and how much they will be affected by earthquake energy. Such studies are very important and useful in determining the seismic codes for buildings (Kanai 1957). In this study, four different geological environments in Egypt were chosen to study the seismic/sound energy transmission properties of different types of soil (Fig. 1). First, a relatively calm soil condition was used to determine the soil properties. After that, seismic/sound energy was increased to study any changes in the soil

properties by using low sound sources such as sledgehammer as well as high sound sources such as a hydraulic hammer. Then sound spectrograms for all cases were produced to study both the soil and source variations. A room was built in the subsurface to observe the performance of trapped sounds inside the empty structures, which, along with subsurface cavities and archeological applications such as subsurface tombs, were simulated to engineer problems. Finally, this method was performed in an old archeological site to test and evaluate the results of this research.

The four selected sites were the EL-Gamil site, located in Port Said city (marine environment with Sabkha deposits), 6th of October site, located in Giza city (thick layers of coarse sand), New Giza (massive limestone interbedded in the thin layers of stiff clay) and Abu Rudeis site, located in the West Sinai (weathered coral limestone).

In this context, we focused on higher frequencies that are audible to the human ear (20–3000 Hz). As the human ear can differentiate between thousands of voices, we may be able to use this sense to identify the type of the soil and other soil properties by listening to the records of the sounds from within the

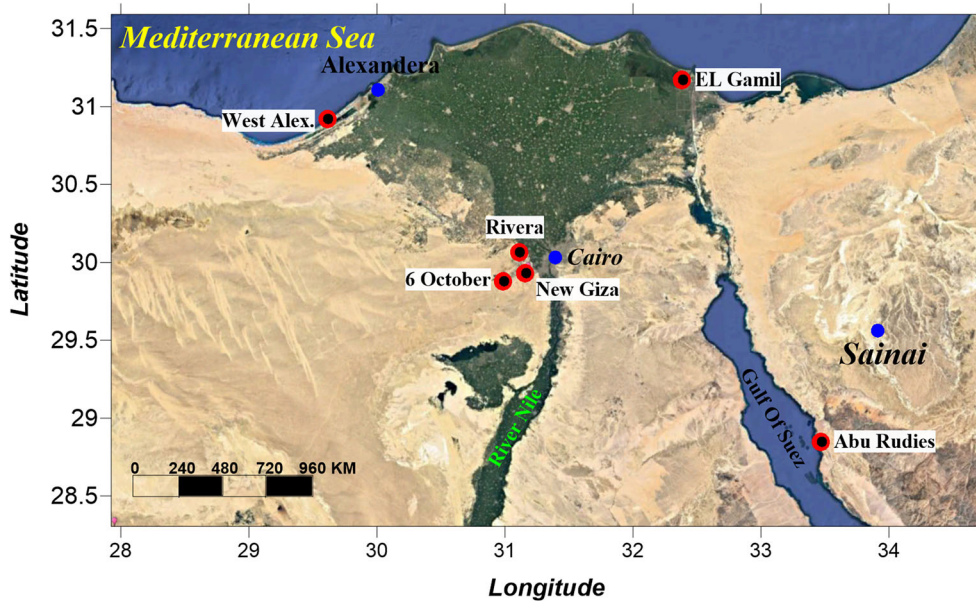


Figure 1  
Soils chosen in Egypt to collect non audible seismic (1–20 Hz)/audible sound (20–4000 Hz)

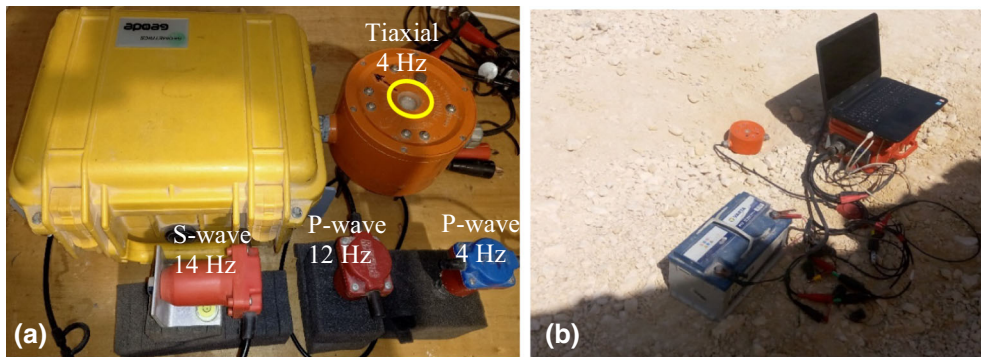


Figure 2

Used equipment in this study Geode 24 Geometrics seismograph (a) and ES 3000 Geometrics seismograph, Triaxial 3 component 4 Hz geophone, 4 Hz P-wave geophones, 12 Hz P-wave geophones, 14 Hz S-wave geophones, 40 Hz and 100 Hz P-wave geophones (it have same shape like 12 Hz but not shown)

soils. In order to do this, high-quality data were collected using highly accurate seismographs, which are capable of collecting high-resolution data (16,000 samples per second) and geophones in 3D (4 Hz tri-axial geophone, 4 Hz P-wave, 12 Hz P-wave, 4 Hz S-wave, 14 Hz S-wave, 40 Hz P-wave, and 100 Hz P-wave. Figure 2).

The high-quality data and spectrograms up to 3000 Hz were used to clearly highlight the changes in the audible sound properties as a result of the variation in the soil type and to determine whether the change was as a result of the change in the soil type or the sources of sound.

## 2. Data Collection and Sites Description

Successfully collecting seismic or sound soil samples is not an easy endeavor and it needs lots of experience. This is most probably due to the fact that the recorded samples are combinations of the sound source properties and soil properties in almost all cases. Thus, one must be patient while collecting each sample and should take an appropriate amount of samples to determine the soil properties as well as the surrounding sources. For this, we recommend the invention of real-time spectrometer instrument that does not exist yet (at least to the best of our knowledge). This complexity may be due to one or more of reasons (for instance, the location of the sound sample; duration of the sound sample; selection of the

proper types of geophones and its frequency according to the soil/source types; surrounding sounds, buildings and constructions nearby the sample; the level of nearby noises of the wind, traffic, and the likes; the crew talking during data collection may cause interference with the sound samples, as geophones can record any sound; the degree of resolution, such as the number of samples per second and the length of the recording, of the data.)

Table 1 gives a brief description for the data collection parameters used in this study.

### 2.1. Abu Rudeis Site (Coral Limestone and Sand)

Abu Rudeis site is located on the Red Sea at the eastern part of the Suez Gulf (Fig. 1), it is mainly composed of carbonate-rich sediments. The soil is composed of brown coral limestone and sand. The standard penetration test was used at each site to determine the relative strength of each soil. Based on the standard penetration test (SPT) value  $N_{30} \geq 50$  (refusal depth-Table 2), the Abu Rudeis site was classified as medium to strong soil. Data were collected at 240 stations distributed over the entire site, 32 records at each station. To do so, 4 Hz P-wave vertical geophones were used; the record length was 2 s, and the sampling frequency was 8000 sample per second. These data were acquired at calm soil and soil that was excited by wind and the impulsive striking of a 10- kg hammer.

Table 1  
Parameters used to collect data for all soil types in this study

Site	Soil	Sound level	Total stations	Records/station	Geophoneused	Record length (Sec)	Sampling. Freq (S/sec)
1. Abu Rudies	Sand/coral L.S	Calm/10-kg Hammer	240	32	P: 4 Hz	2	8000
2. EL Gamil	Soft/stiff clay	Calm/generator	40	80	4 Hz downhole triaxial	0.5–2	8000–16,000
3. New Giza	L.S/stiff clay	Calm/hydraulic hammer	20	30	4 Hz surface triaxial	2	8000
4. 6th October	Silty sand	Calm/cars on road	60	80	4 Hz surface triaxial	2	8000
5. Rivera	Sand with clay	Calm/wind	20	30	4 Hz surface triaxial	2	8000
6. West-Alex	Coral L.S	Calm/wind	12	40	P: 4–40–100 Hzs S: 14 Hz	2	8000

Table 2

Comparison between relative soil strength derived from SPT test refusal depth ( $N_{30} \geq 50$ ) and maximum pitch frequency obtained in this study

Soil name	Main soil composition	Maximum “resonance pitch” obtained by soil (Hz)	SPT soil refusal depth (m)	Relative strength
EL Very weak	Gamil-1	Soft Clay	8	20
Rivera	Sand with clay	30	9	Weak
6th of October	Silty Sand	70	70	8
West of Alex	Coral L.S	80	–	Medium
Abu	Rudies	Sand/Coral L.S	200	5
EL	Gamil-2	Stiff Clay	950	4
New Giza	Limestone	2900	–	Very strong

## 2.2. El Gamil Site (Soft Clay or Stiff Clay)

El Gamil site is located in the north-eastern part of Egypt on the Mediterranean Sea (Fig. 1). The climate of the area is similar to that of typical coastal zones. The site is surrounded by weak Sabkha deposits. Two

samples were taken at this site, one over the soft deposits and the other over silty sand underlain by stiff clay. The stiff clay usually tends to behave like a weak rock in terms of seismic velocity. Based on SPT refusal depth value  $N_{30} \geq 50$  (Table 2), El-Gamil soil was classified as very weak to medium. Data were collected at 40 stations: 20 over soft soil, and 20 inside the well (20 m depth). There were 80 records at each station. Downhole triaxial geophones of 4 Hz were used over the soft soil and 4 Hz downhole geophone inside the PVC air-filled tube was used inside the medium soil. The record length ranged from 0.5–2 s, and the range of the sampling frequency was 800–16,000 samples per second. These data were acquired at calm soil and soil excited by an electric generator.

## 2.3. New Giza Site (Massive Limestone Intercalated with Stiff Clay)

New Giza site is located in the western part of the Nile River and Egypt’s capital Cairo (Fig. 1). This area is a part of a very big famous structure called EL-Hassana Dome, a big dome mainly composed of thick massive limestone intercalated with stiff clay (Said 1990). Of course, the SPT was not made inside rocks. However, New Giza’s soil was classified as the strongest among the other soils in this study, as the site is formed of massive thick layers of high-quality



Figure 3

The Hydraulic hammers which were used to generate higher level of seismic/sound energy during data recording at New Giza Site

limestone that could hardly be broken using hydraulic hammers (Fig. 3 and Table 2). Data were collected at 20 stations with 30 records from each station; a 4 Hz triaxial geophone was used. The record length was 2 s, and the sampling frequency was 8000 samples per second. These data were acquired at calm soil and soil excited by a hydraulic hammer.

#### 2.4. 6th of October Site (Silty Sand)

The 6th of October site is located inside 6 October city, a newly developed urban area that was also constructed in Giza Governorate. It is located to the west of Cairo city in the north-central part of Egypt (Fig. 1). The 6th of October site is mainly composed of dense sand, silty sand, and silty clay sand. Its soil strength was classified as medium based on the SPT refusal depth value ( $N_{30} \geq 50$ ) (Table 2). Data were collected at 60 stations over calm soil and the soil surrounded by buildings with 80 records from each station. A 4 Hz triaxial geophone and a 4 Hz P-wave vertical geophone were used, the record length was 2 s, and the sampling frequency was 8000 samples per second. These data acquired from calm remote soil and soil surrounded by buildings.

#### 2.5. Rivera (Sand with Clay)

The subsurface model was built in Rivera city. It was an empty room built on the subsurface of dimensions  $4 \text{ m} \times 2 \text{ m} \times 3 \text{ m}$  and covered by concrete and iron (Fig. 4). The model is designed to

calibrate the effect of sound transmission in a subsurface inside empty closed structures. Later, this will be used to recognize similar structures such as the subsurface of dangerous cavities or archeological tombs. This site was recently constructed in Giza Governorate (Fig. 1). It is located to the west of Cairo in the north- central part of Egypt. The soil is mainly composed of silty sand and, therefore, it is considered weak based on SPT refusal depth value ( $N_{30} \geq 50$  Table 2). Data were collected at 20 stations distributed over the soil and the room built in the subsurface with 30 records from each station. A 4 Hz triaxial geophone was used, the record length was 2 s, and the sampling frequency was 8000 samples per second. These data were acquired at calm soil and soil excited by wind.

#### 2.6. West of Alexandria Site (Weathered Coral Limestone)

West of Alexandria site is located at about 45 km away from Alexandria city. This site is located on Mediterranean Sea and about 1200 m away from the sea. It is mainly composed of coral limestone. The recording was done in a subsurface room that could remained one of an old tomb. No. SPT data were available to West of Alex site, as it is made of thick layers of coral limestone rocks. However, it typically has higher bearing soil rather than clay and sand (Table 2). Data were collected at 12 stations with 40 records from each station. To do so, 4 Hz, 40 Hz, and 100 Hz P-wave geophones and 14 Hz S-wave

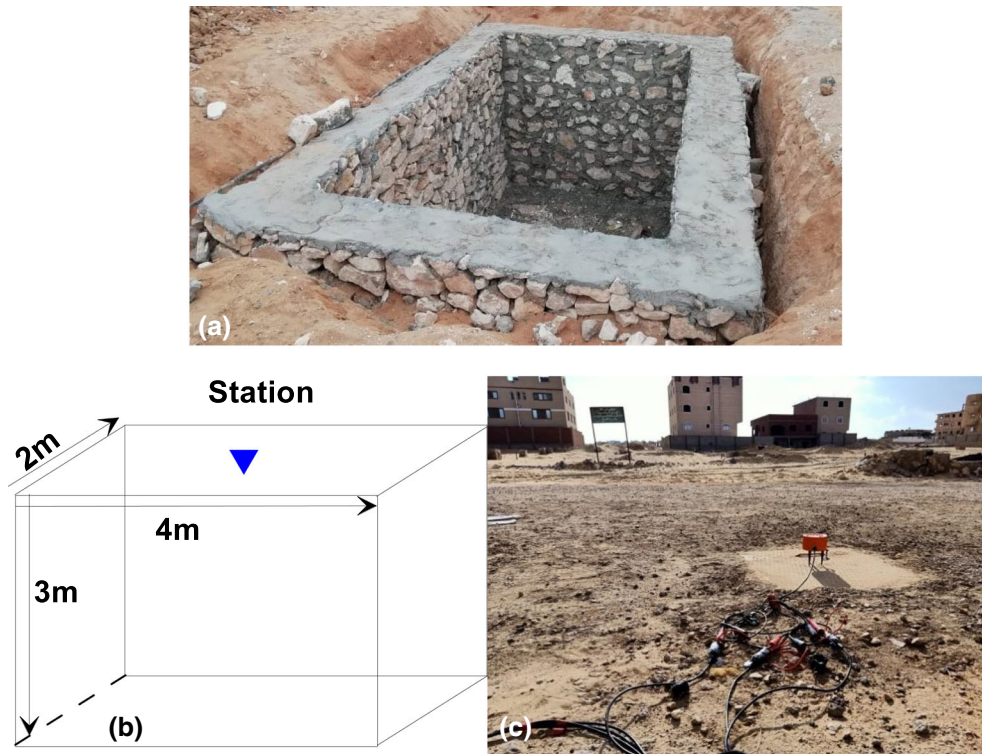


Figure 4

A sketch shows an empty room built on the subsurface (a), its dimensions (b) and how it was covered by iron cover, and samples were taken (c)

geophones were used, the record length was 2 s, and the sampling frequency was 8000 samples per second. These data were acquired from within the soil excited by wind (Fig. 5).



Figure 5

The empty tomb that was discovered after the sound record was collected in west of Alexandria area

### 3. Methodology and Data Processing

#### 3.1. Data Acquisition

Different geophones such as P-wave geophones with frequencies of 4 Hz, 40 Hz, and 100 Hz, S-wave geophones with frequencies of 4 Hz, triaxial 4 Hz geophones, and downhole triaxial geophone were used in this study. In each site, we carefully got rid of any unwanted external sources of noise or sound while recording calm soil conditions. For excited soil conditions, we tried to ensure that there was just one source of excitation to avoid any confusion in the data. In order to get audible sounds, we kept the recorded signals as small as 0.5 or 2 s to get high samples ranging from 8000 to 16,000 for each record. To showcase the true effect of each soil, a significant number of records were collected from each station as described in Table 1. For quality control over the data, a lot of stations were distributed over each site with different conditions, such as calm, noisiness,

remote areas, areas surrounded by buildings, etc. The geophones were implanted in order to get rid of the wind noises as much as possible, and we used only firm soil conditions for good coupling with the geophones.

### 3.2. Data Processing

The following main processing steps were implemented on the “seismic/sound” records:

- Convert the data from seg2 format into standard Ascii formats,
- Merged all collected data into one segment signal,
- View the signals in the time domain (Fig. 6) and delete the unwanted sound peaks (such as sudden strikes) if necessary,

- Cut the unwanted sources of sounds (hammers, falling objects, sounds of nearby cars, airplanes or any moving objects), which can affect the natural formants of soil pitches, to produce calm soil conditions,
- Create programs or codes that are capable of producing high-quality “seismic/sound spectrograms” with full control over the parameters to calculate it such as:

- (a) Use the ability to change the size of the window to calculate the “seismic/sound spectrogram,”
- (b) Use the ability to change the size of the overlap window,

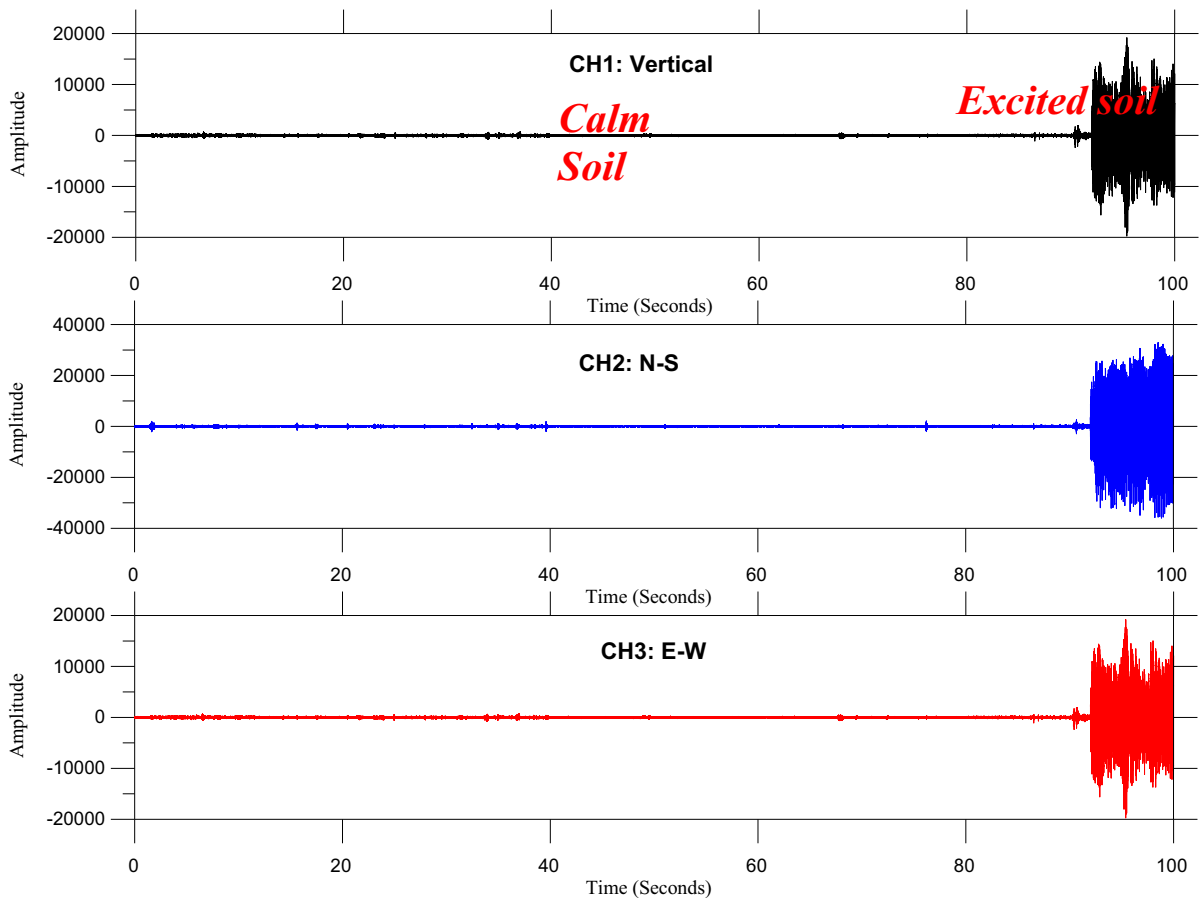


Figure 6

A sample of record in New Giza site shown the variation at calm soil when it was excited with a strike of hydraulic hammer

- (c) Use the ability to change the method to calculate the spectrogram (Rectwin, Gauss, Blackman, etc.),
  - (d) Compare the different directions of the spectrograms such as vertical or horizontal channels,
  - (e) Use the full control over color, time, frequency, and possibility to cut the bad parts and save the best parts of the data,
  - (f) Transform the clean data into spectrograms with a window size of 8000 samples or 3000 samples,
  - (g) The overlap between the samples is 70% or more depending on the quality of the produced spectrogram,
- Type of spectrogram used (Blackman, Gauss, Rectwin, etc.) acts as the lens of the camera, which may generate either very clear pictures or very bad pictures, Hence, the program was used to get the best spectrogram for each soil.

#### 4. Results

In 1990, Field and Jacob introduced an important model for describing the difference between calm and excited soil by using a “pile-driving” machine with a seismic frequency range (1–12 Hz). The study showed that increasing seismic energy will insert new seismic frequencies inside the soil in addition to the original natural resonance frequency of the soil (Fig. 7). These new frequencies are easily seen near the source, but far from the source energy, it is concentrated only in the natural frequency of the soil vibration. This is natural, as the energy attenuation is far from the source (Fig. 7). In this study, we will show the variations in “seismic/sound spectrograms” as a result of the difference in soil conditions with more focus on the sound frequency ranges, which are audible to the ear in the range of 20–3000 Hz.

The following is a summary of the entire data collected from about 172 stations that were distributed all over the different sites.

##### 4.1. Abu Rudeis Site

The soil found in Abu Rudies site can be considered to be of medium strength, as the sand has existed for a long time and its constituent coral limestone rock has eroded over time. A hammer was used to excite the soil. The calm soil conditions show that the fundamental natural frequency of vibration of the soil is between 4 and 5 Hz. When the soil is excited with the hammer, the fundamental natural frequency of vibration of the soil remains the same (4–5 Hz), but with a higher amplitude as a result of more impactful hammer strikes, new frequencies were inserted inside the soil, as proposed by Field and Jacob (1990) (Fig. 8).

A spectrogram was calculated for the same data for Abu Rudies site that was quit close to the hammer source (Fig. 9). Here, we can see the magnificent effect of the energy distribution inside the soil due to the hammer strike. As can be seen, the maximum energy of the hammer strike occurs at about 40–60 Hz. This is most probably due to the nature of the energy generated by the hammer. It can also be seen that the vibrations of the hammer enter some energy into the soil at the seismic range of 1–10 Hz and, especially, at the natural frequency (4–5 Hz) of the soil vibration (Fig. 9). This is one of the most distinctive things that could not have been seen in the traditional Fast Fourier Transform (FFT) but can be seen here. The energy or the fundamental natural frequency of vibration of the soil is not fixed and changes fluctuates a little due to the energy triggered by the hammer (look to 5 Hz fluctuation in Fig. 9). By magnifying the picture of the spectrogram in the seismic frequency range of 1–20 Hz, we can see the energy of the hammer is divided into 5 Hz, 8 Hz, and 12 Hz. It should also be noted that the fluctuation of the energy is in a winding line rather than a straight line at each energy level due to the impact of the hammer strike (Fig. 10). The spectrograms for the geophones, located at an intermediate distance of about 50 m from the source of the explosion, shows that the effect of the hammer explosion still exists at 50 Hz (Fig. 11). The hammer strike injects various energies at levels 50 Hz, 120 Hz, 160 Hz, and 200 Hz, which are audible to the human ear and can be recognized upon hearing. As the distance from



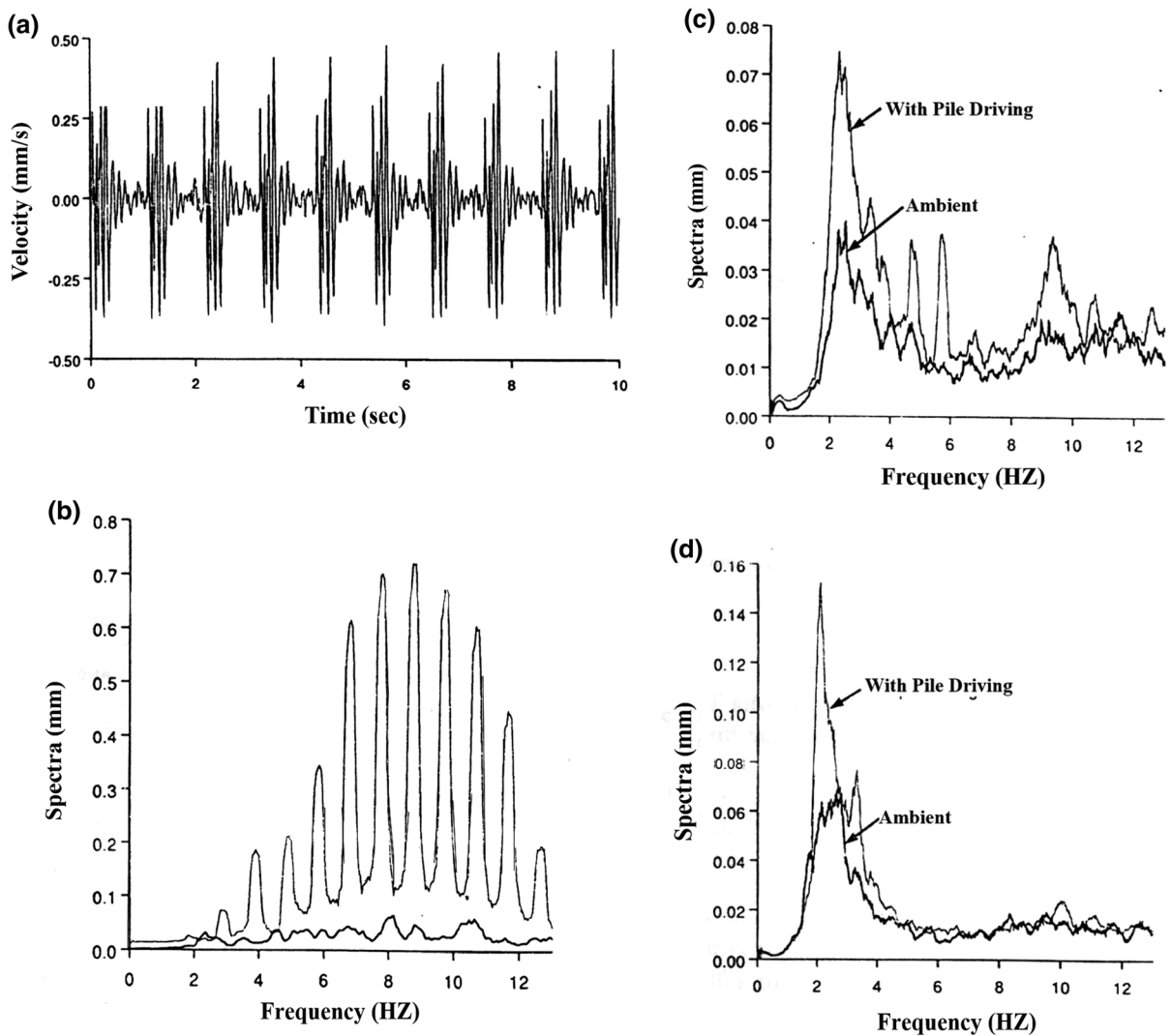


Figure 7

Change of soil natural frequencies of vibration using pile driving machine. **a** Pile driving machine signal in the time domain, **b** spectrum of the pile driving machine, **c** the spectrum of soil near to the pile driving machine showing new peaks and **d** spectrum of soil far from pile driving machine showing the original soil resonance peaks (Field and Jacob 1990)

the explosion source increases to about 100 m, the calculated spectrograms show that the source effect becomes weaker. This can be normally expected, as the energy attenuates due to an increase in the distance from the source. The remaining energies are found at the natural soil frequency at 5 Hz and 10 Hz and the source frequency at about 50–60 Hz (Fig. 12). It is worth mentioning here that when the sound recorded at the Abu Rudies site is played, it produces an intermediate pitch sound that reaches up

to 200 Hz. This is the sound of vibration in the soil of medium strength.

#### 4.2. EL Gamil Site

The first sample of the El-Gamil site was taken over very weak soft soil that is mainly composed of soft clay (Fig. 13). The soil resonance frequencies or sound pitches found here are very low at about 1–8 Hz. These pitches cannot be heard with the

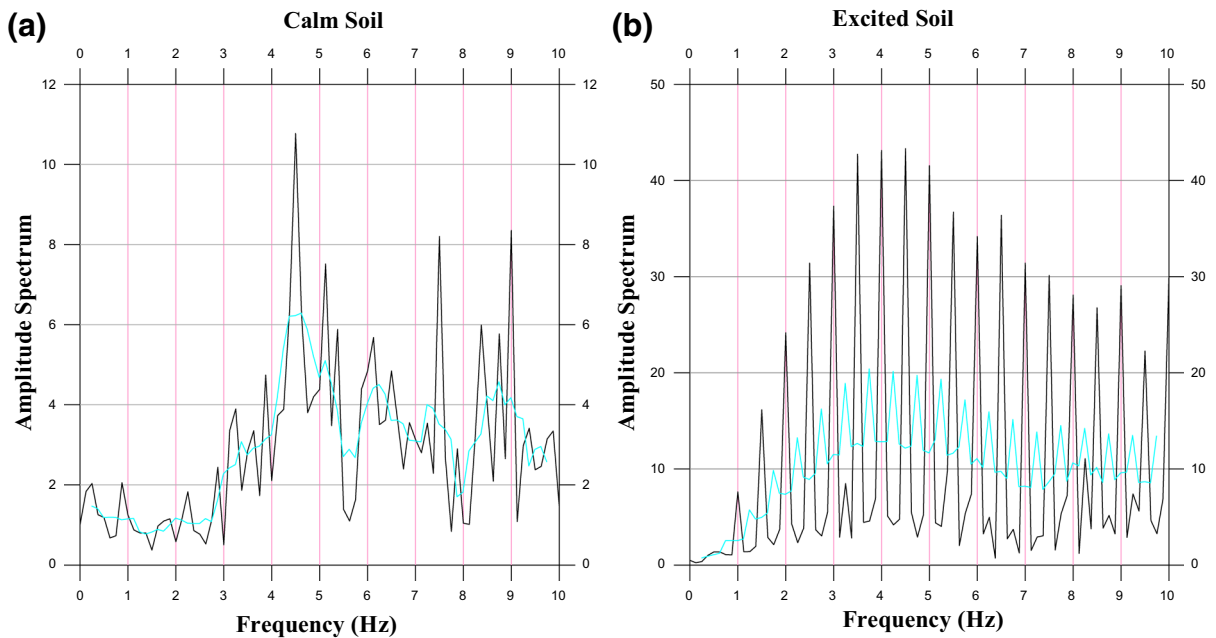


Figure 8

Fourier spectrum for Abu Rudies site in both conditions **a** calm soil and **b** excited soil by impulsive hammer. Note the difference in the amplitude of the spectrum as a result of energy increase. Note also the new frequencies inserted by the hammer strike (cyan line is a running average filter every five points)

human ear. This sound is typical of a very weak soil that is composed of very soft deposits. Another sample from EL-Gamil site was taken over silty sand

underlain by stiff clay. It was taken inside a 4-inch PVC tube filled with air. A lots of resonance frequencies or pitches can be seen here due to air

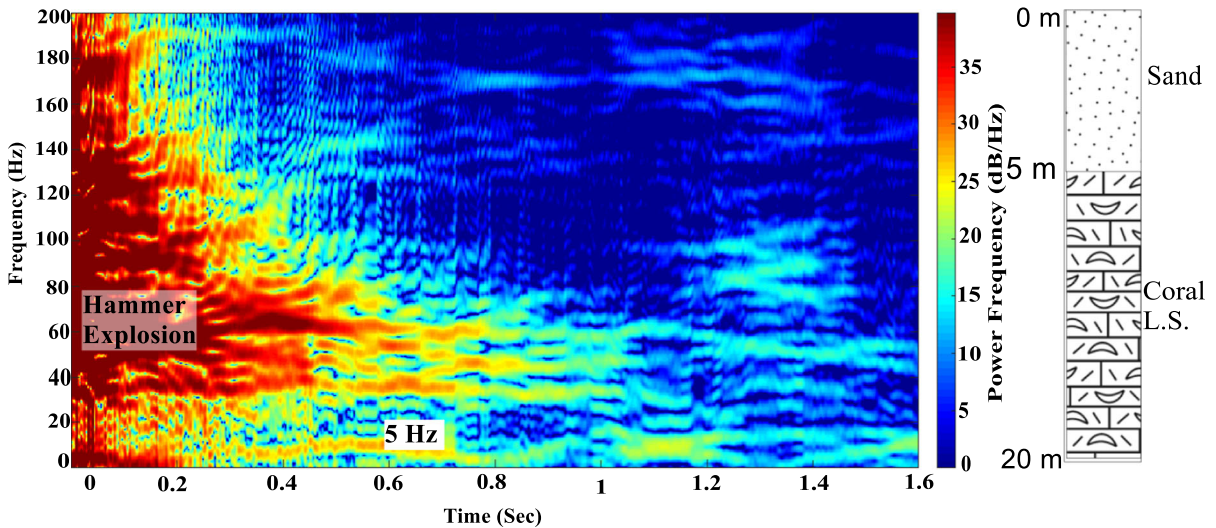


Figure 9

Near sources spectrogram (Geophone is 2 m from source) for Abu Rudies site for high frequency range (0–200 Hz) showing the distribution of the hammer energy with maximum hammer effect at about 40–60 Hz (Audible to ear). Note the fluctuation of energy up and down at 5 Hz

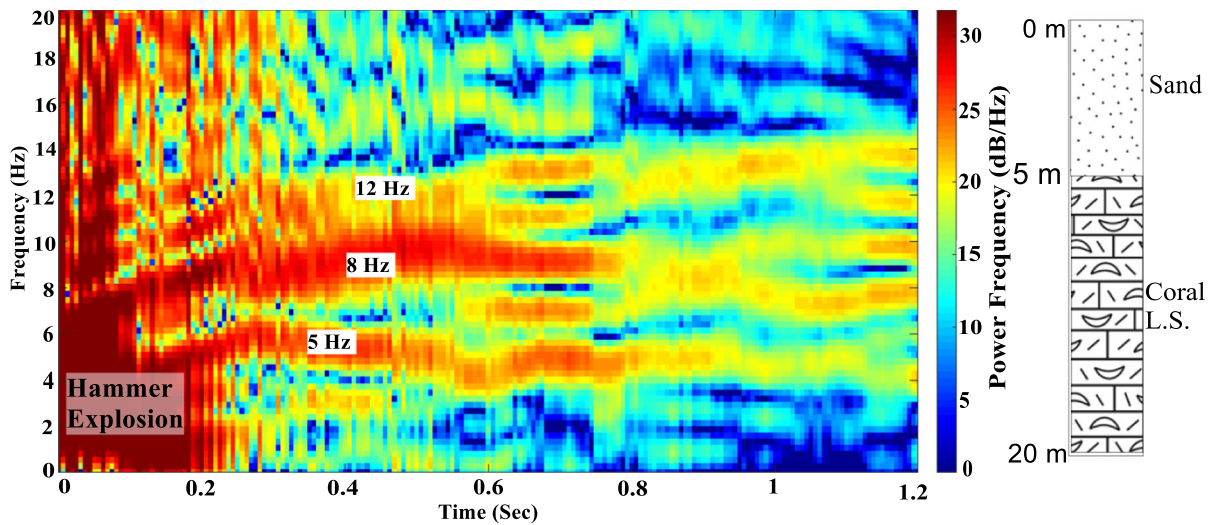


Figure 10

Zoomed spectrogram for Abu Rudies site (at distance 2 m from source) in the frequency range (0–20 Hz) showing the hammer energy enters in frequencies 5 Hz, 8 Hz and 12 Hz (these frequencies are inaudible to ear). Note the fluctuation of energy in a winding line rather than fixed or a straight line

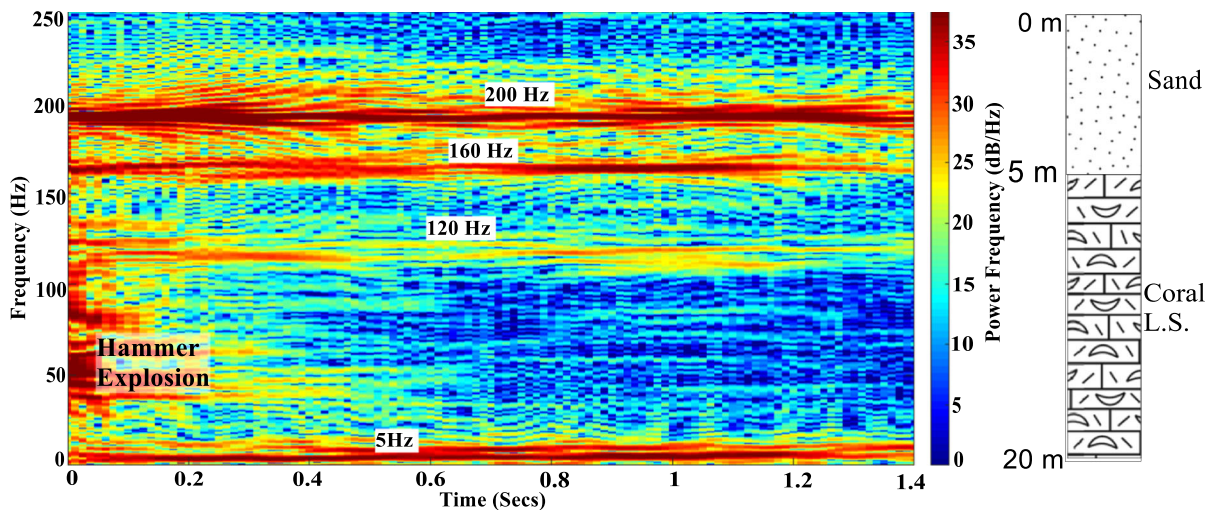


Figure 11

A spectrogram taken at distance about 50 m from the source, for Abu Rudies site showing the hammer source inject various energies at levels 5 Hz, 50 Hz, 120 Hz, 160 Hz and 200 Hz (Frequencies are audible to human ear)

ringing inside the tube particularly at 60, 100, 150 and 200 Hz (Fig. 14). We can notice that the natural resonance frequency of the soil is unclear (1–8 Hz). This is most probably a result of masking by the higher frequency energy. When the soil is excited with electric power generators, the soil shows higher

new frequencies that reaches 950 Hz (Fig. 15). With this information, it can be concluded that the existence of stiff clay has dramatically changed the soil properties. When the sound of the stiff clay sample recorded at the El-Gamil site is played, it produces an intermediate pitch sound that reaches up

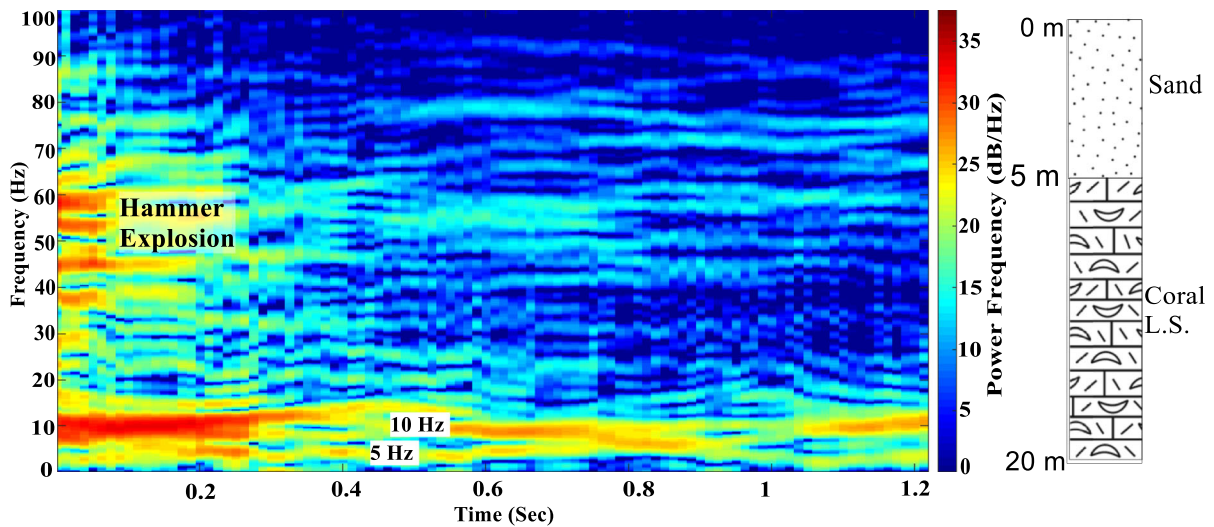


Figure 12

A spectrogram taken at a distance about 100 m from the source, for Abu Rudies site showing the hammer source effect became weaker. It can only inject energies at levels 5 Hz and 10 Hz in the soil and little energies at levels 50–60 Hz

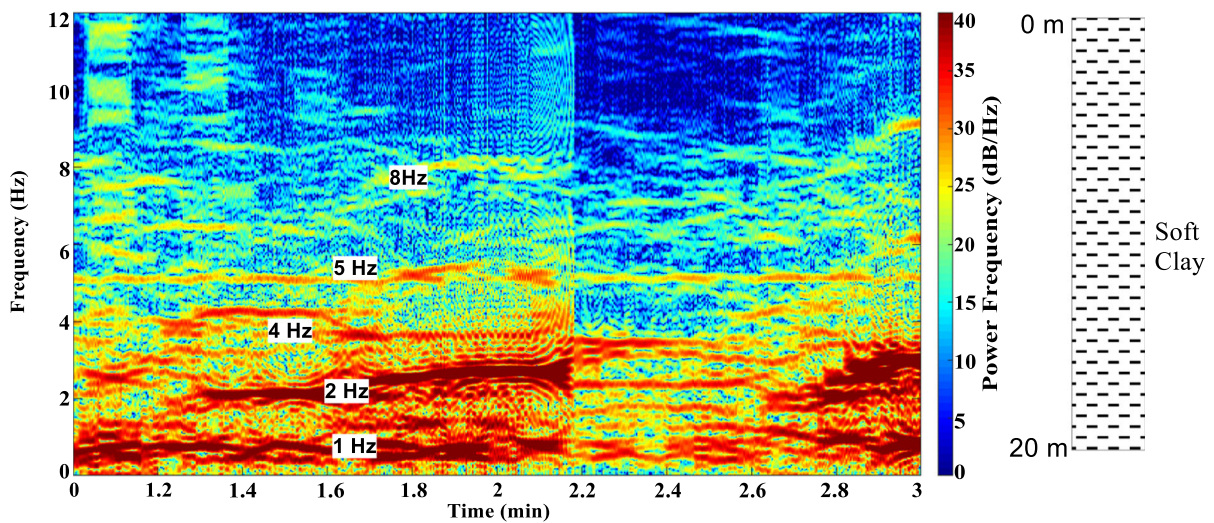


Figure 13

Spectrogram of the first sample of EL Gamil site recorded over weak soft clayey soil showing low resonance pitches at 1, 2, 5 and 8 Hz which is a low pitch sound cannot be heard by human ear

to 200 Hz. This supports the notion that when soil becomes stronger, the resonance pitch becomes higher.

#### 4.3. New Giza Site

It has been determined that the soil at the New Giza site is strong since it is mainly composed of massive thick layers of limestone rock interbedded in stiff clay. The calm soil samples at New Giza show a

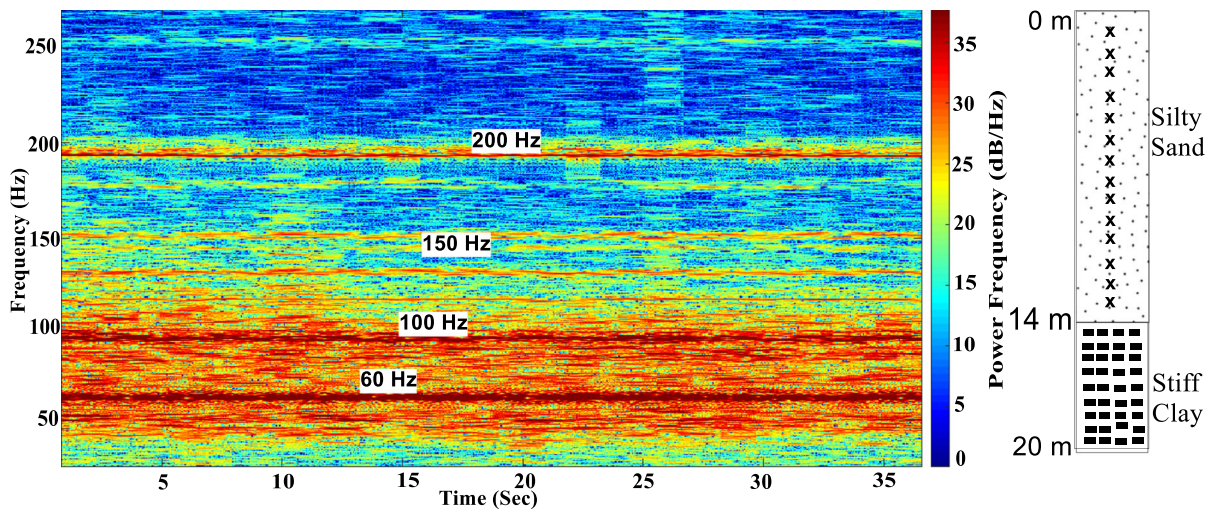


Figure 14

Spectrogram of the second sample of El Gamil site taken over stiff clayey soil showing lots of resonance frequencies or pitches at 60, 100, 150 and 200 Hz most probably due to ringing of air winds inside the PVC tube and the noises from the surrounding machines

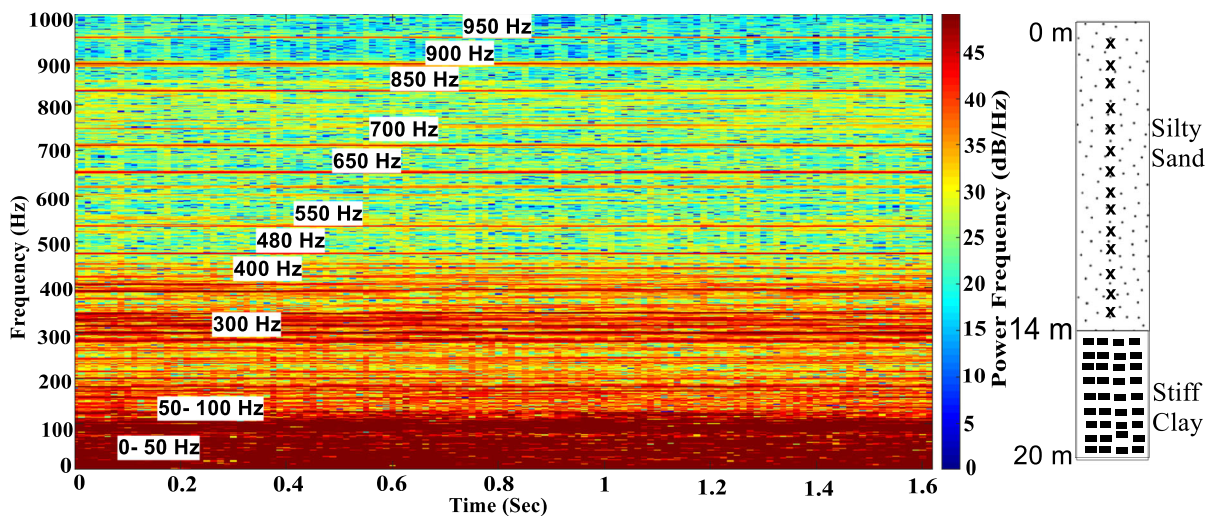


Figure 15

Spectrogram of el Gamil soil after its excitation with electrical power generators at distance about 3 m, a new frequencies generated inside the PVC tube which acts in this case behave a music machine (e.g. a violin)

relatively high-resonance frequency that reaches up to 200 Hz (only first 150 Hz are shown in Fig. 16). When the soil of the site was excited to high energy from hydraulic hammers, the resonance pitches increased to about 2900 Hz (Fig. 17). The sound of

the New Giza site produces a high pitch sound in both calm and excited conditions with frequencies that reach up to 2900 Hz, representing a high soil strength.

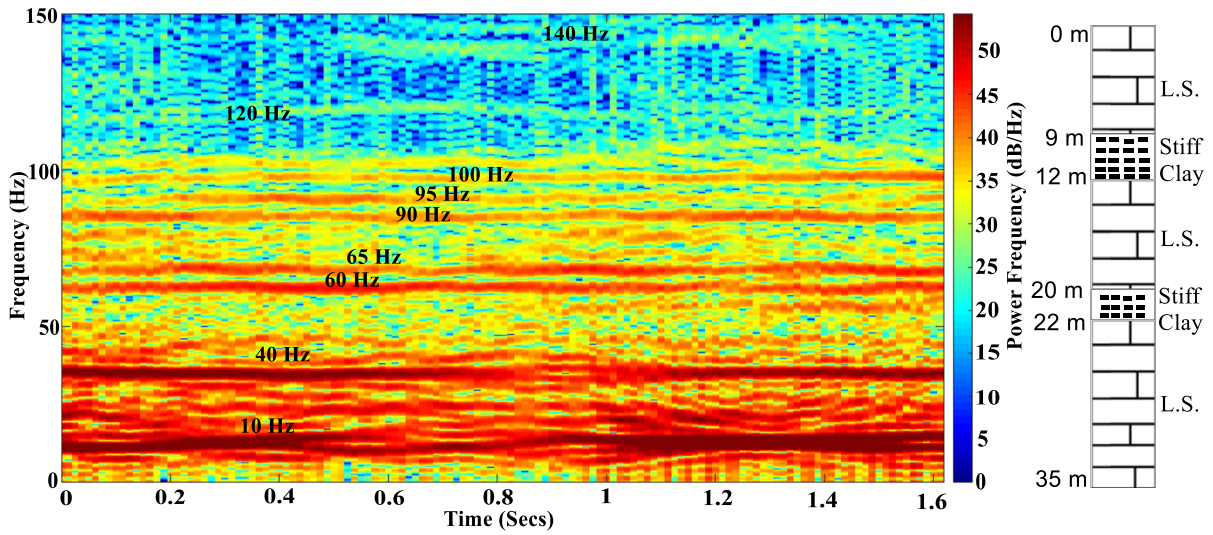


Figure 16

Spectrogram of the calm soil of New Giza site with resonance frequencies at 10 Hz, 40 Hz, 60 Hz, 65 Hz, 90 Hz, 95 Hz and 100 Hz

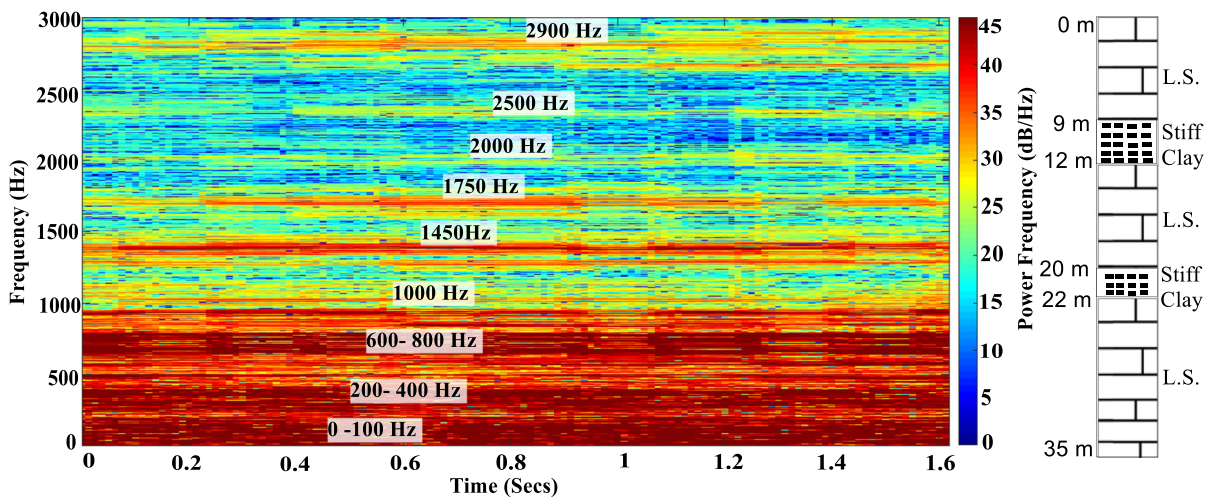


Figure 17

Spectrogram of the excited soil of New Giza site with resonance frequencies at 0–800 Hz, 1000–2900 Hz

#### 4.4. 6th of October Site

Two sound samples were taken for 6th of October site. One was taken over the soil, and the other sample was taken on the 5th floor of a building over the same soil. The horizontal distance between the two samples was around 50 m. The soil of this site is found to be of medium strength (Table 2), mainly

composed of silty sand intercalated with thin layers of silty clayey sand. The sample was recorded from the station over the soil and exhibited seismic resonance frequencies at 1–10 Hz and sound frequencies of about 35 Hz (Fig. 18). However, the sample collected on the 5th floor inside the building showed different sound resonance frequencies (22 Hz, 38 Hz, 50 Hz, and 70 Hz). These new sound

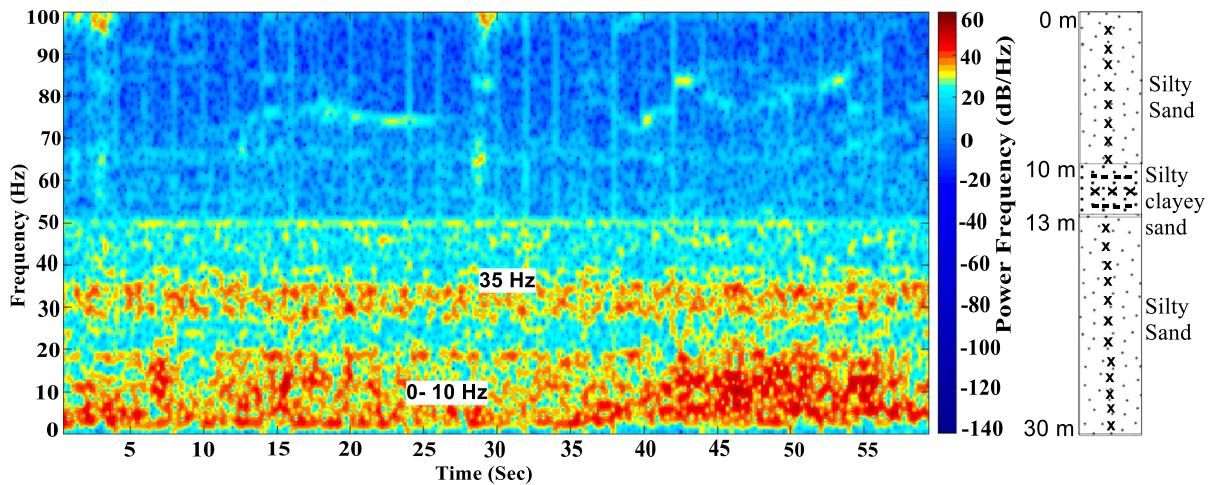


Figure 18

Spectrogram for 6th of October soil showing resonance frequencies at 0–10 Hz and 35 Hz. Note the frequency at 50 Hz is most probably due to the nearby building

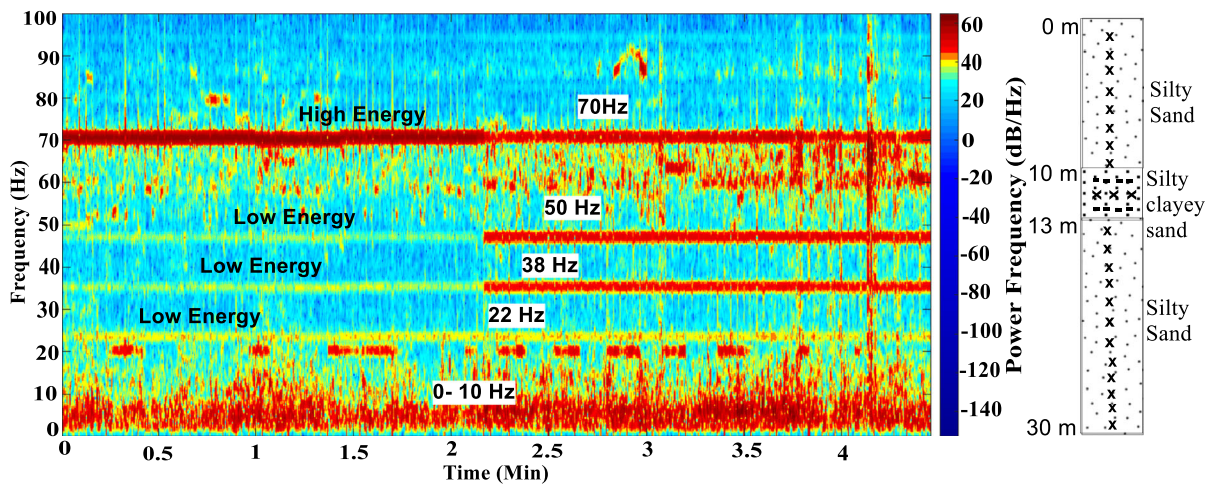


Figure 19

Spectrogram of 6th of October building taken at the 5th floor over the same soil showing resonance frequencies at 35 Hz, 50 Hz and 70 Hz due to transmission and amplification of sound inside the building. Note the existence of faint “Energy levels” exists at 0–2.2 min for frequencies 22 Hz, 38 Hz and 50 Hz prepared to accept energy

frequencies are most probably different due to the sounds transmitted from inside the building itself (Fig. 19). One of the magnificent phenomena that was realized at this site is the phenomenon of “energy levels” where the energy with the resonance frequencies 22 Hz, 38 Hz and 50 Hz for a duration 0–2.2 min are very weak in terms of power (dB/Hz). However, after 2.2 min, for the same frequencies, the energy became higher. This can support the idea that

soils may have “energy levels” just like atom that preserve levels to accept energies, and this is dependent on the nature of the site rather than the sound source.

#### 4.5. Rivera Site

In order to study the difference between sound transmissions inside soil and geological structures

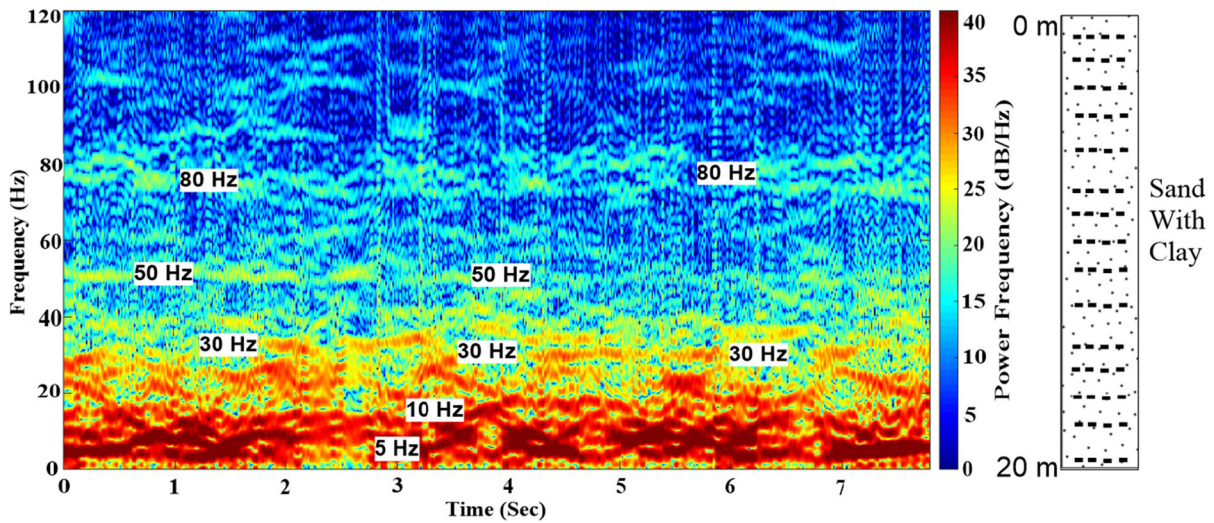


Figure 20

Spectrogram of Rivera soil shows the natural frequencies of vibration at 5 Hz to 30 Hz. Note also little number of pitches with irregular shape 0–30 Hz

such as cavities, a buried empty room was constructed and covered with a concrete ceiling inside the soil of EL-Rivera city (Fig. 4). Two samples were taken from the site at a little time difference of 10 min. One of the samples was taken from over the soil and the other over the buried room at a horizontal distance of about 20 m. The soil of EL-Rivera city is considered to be relatively weaker than the ones from the other sites (Table 2). It is mainly composed of sand which is mixed with clay. The sample taken over the soil has low sound pitches of frequencies 5–30 Hz with an irregular shape (Fig. 20), while the sample taken over the built room has more frequencies (50 Hz, 90 Hz, 30 Hz, 140 Hz, 160 Hz, and 220 Hz) that are more clear, regularly shaped, and energy. This is considered a dramatic change in both the levels of resonance pitches and sound energy (Fig. 21). If the sound of Rivera soil is played, it will produce a low sound that can barely be heard, whereas the sound recorded over the room will produce distinct sounds that have higher pitches and energy. This new sound is completely different from the sound of the soil and can be recognized and distinguished well by human ear. Therefore, with that in mind we can conclude that due to the presence of cavities and subsurface structures, the sound inside the soil changes, giving out higher tones and energy,

and they can also easily be recognized by the human ear. This is similar to what happens when sound resonates inside musical instruments such as a violin.

#### 4.6. West of Alexandria Site

In order to apply our findings, we went to the west of Alexandria city, a place that is famous for subsurface tombs. The site is formed of rock of coral limestone of low strength. In this site, we recorded a sample over the soil. The sample had a unique resonance frequency with a very sharp pitch at 25 Hz (Fig. 22). We kept doing this until we found a similar resonance effect as found earlier over the model built by us (Figs. 23). At 5 Hz, 20 Hz, 40 Hz, 60 Hz, and 80 Hz, the resonance frequencies, with sharper and more continuous effects, were even more distinctive than the ones we found in our model. After that an empty room was discovered in the location at which the ground was singing (Fig. 5 and Fig. 23). We concluded that the singing of the ground, as shown in Fig. 22, was a part of or related to the singing of the ground that was discovered over the buried room (Fig. 23). We can say the more resonance pitches or singing of the ground can be found, the higher the possibility of finding cavities or tombs in the subsurface. This is most probably due to resonance



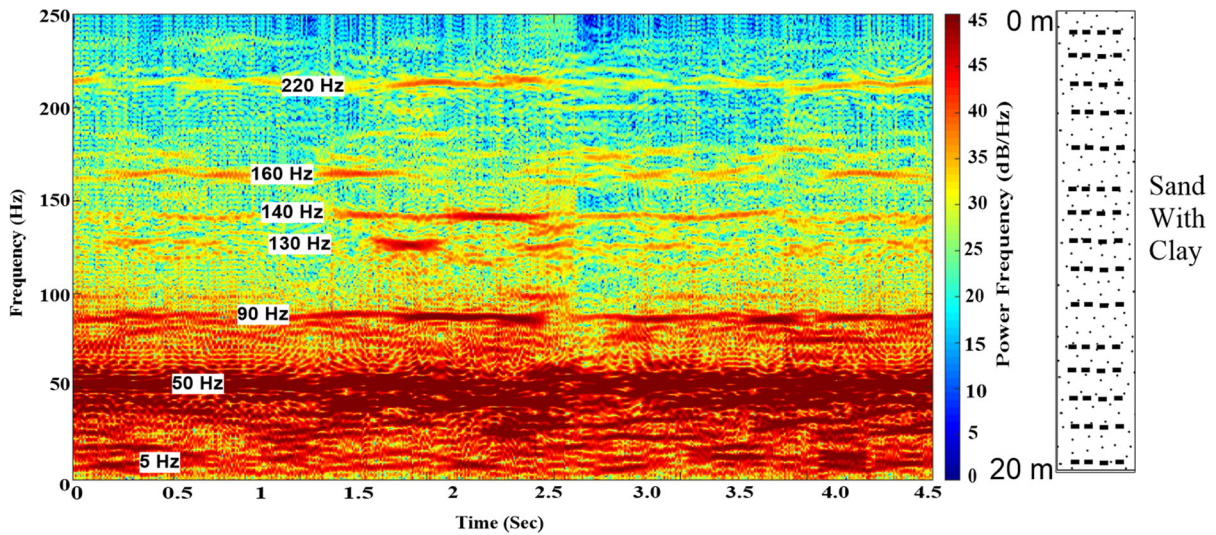


Figure 21

Spectrogram of the buried empty room in Rivera city has more frequencies (50 Hz, 90 Hz, 130 Hz, 140 Hz, 160 Hz and 220 Hz) that are more clear, regular, and higher energy due to the sound resonance inside the room (sensor is placed over iron door)

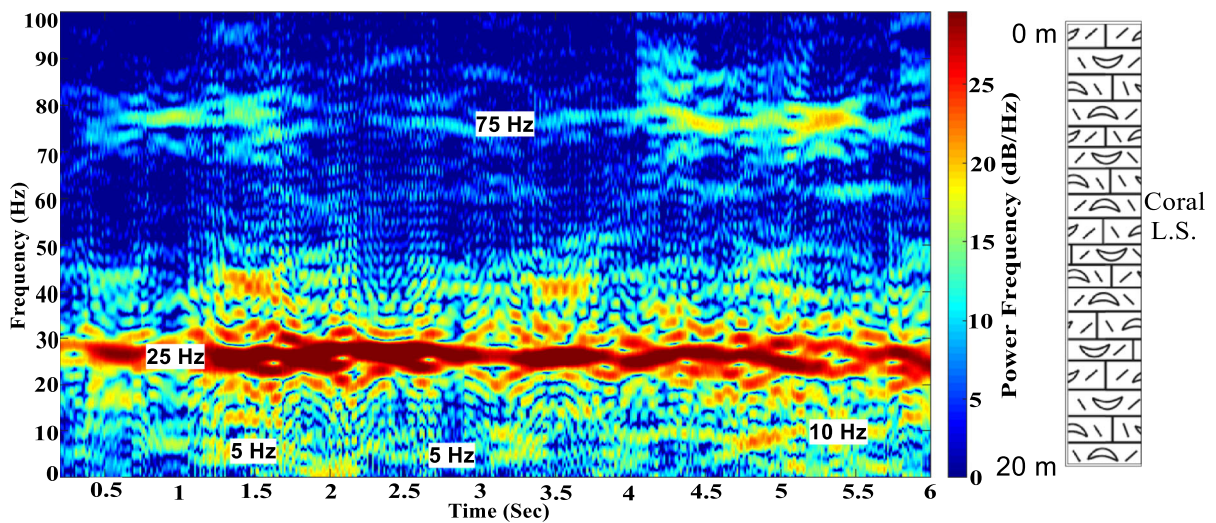


Figure 22

Spectrogram taken in the beginning of the recording at West of Alexandria site showing distinct sharp tone of sound at 25 Hz. This was taken as an initial evidence of the existence of subsurface empty structure in this region

of sound inside the closed empty spaces. It is important to mention here that we highly recommend taking advantage of this phenomenon and making a new geophysical instrument that can help in

conducting archeological researches or cavity detection. This can be done by showing high-quality spectrograms in the field and following the resonance of sounds in order to locate cavities or buried rooms.

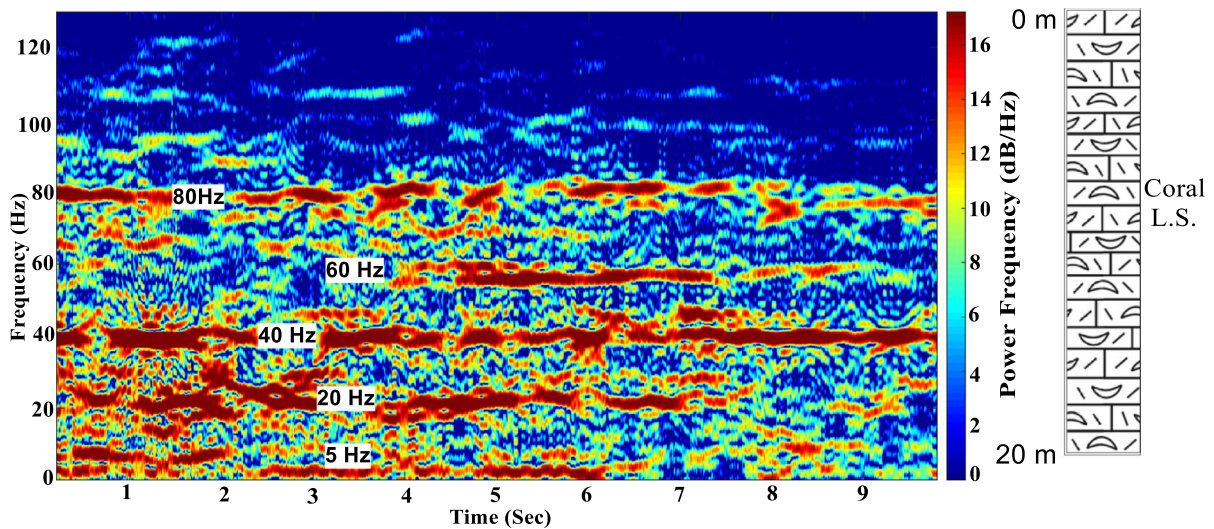


Figure 23

As we approached the location of the room the resonance pitches frequencies became clearer and higher energy at (5 Hz, 20 Hz, 40 Hz, 60 Hz and 80 Hz) that is most probably due to the sound resonance inside the empty room

### 5. Summary and Conclusion

For studying the properties of audible sound inside soil, we have recorded samples at 172 stations for both calm and excited conditions of soils of different types ranging from very weak to very strong soil. The recordings were taken in different directions—one vertical and two horizontal directions. The data were collected with high accuracy using high-quality seismographs that are capable of collecting more than 16,000 samples per second and using geophones of different directions (P-wave and S-wave geophones) with frequencies ranging between 4 and 100 Hz. A special programming code was created in order to calculate the seismic/sound spectrograms with full control over the parameters that were used to calculate the spectrograms such as window size, overlap between the windows, and type of spectrogram that has been used. This helped us to get clear pictures of the sound transmission and different properties of various types of soils and produce high-quality spectrograms of up to 3000 Hz in order to clearly show that the change in the audible sound properties is as a result of the change in the soil type. We were able to differentiate between the changes in the sound as a result of a change in the soil type and sound source. We found a relation between the sound

pitch and strength of the soil, where the maximum pitch of the sound recorded inside the soil is a function of the soil strength. As the pitch increases, the strength of the soil increases. Even when the same soil strengthened due to a change in chemical composition (like in the El-Gamil site), its pitch increased from low inaudible pitches to high pitches that are audible to the human ear. These properties of high-frequency audible sound pitches were difficult to be seen in the traditional FFT spectra, but they can easily be seen in high-quality seismic/sound spectrograms. We found that the natural frequencies of vibrations (pitches) in the soil are not fixed, as they fluctuates a little due to the change in sound energy that is introduced in the soil. The energy enters the soil in a winding line rather than in a fixed or straight line like in the traditional FFT spectra. This may support the idea that soils have “energy levels” like atoms that preserve levels to accept energies, and this is the nature of the site, not the source. The empty subsurface room was built in the Rivera site to show the properties of the sound transmission inside empty closed structures. The model showed that the soil has low sound pitches, whereas the sounds in an empty room have more frequencies that are clearer and have more regular shapes and higher energies. It can exhibit a significant unique effect when played, as the

sound can be easily recognized from the surrounding soils. This can be considered a dramatic change in both the levels of resonance pitches and sound energy. The presence of cavities and subsurface structures may result in a change in the sound with higher tones and energy that can easily be recognized by the human ear. This is similar to what happens when sound is trapped and resonates inside musical instruments, such as a violin, due to the resonance of sound inside the corners of the violin box. This property was used to find the location of a subsurface old empty tomb in the West of Alexandria site. “Soil sound properties” are physical properties that cannot be changed unless some chemical or physical properties of the soil are changed. The sound in the soil is found to be proportional to its strength. Thus, it may be used to identify its strength and type in the future. The variation of sound within the same soil may be used also to locate subsurface structures, such as voids, cavities, or even subsurface tombs as it was done in the west of Alexandria. Transforming the soil properties to produce sounds that can be heard by the human ear may be possible with new discoveries regarding earth properties. Furthermore, more research work in the field of “soil sounds” can be promising for the following fields:

- In engineering applications such as the change in buildings’ strength and properties and the study of energy distribution inside it,
- In determining the soil type and strength using sound,
- For seismological applications such as soil/structure interaction studies,
- In identifying geological hazards such as subsurface cavities, sinkholes, landslides areas, avalanches and volcanoes,
- For oil prospecting and water exploration by identifying their voice fingerprints,
- For archeological applications.

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