Estimating the near-surface site response to mitigate earthquake disasters at the October 6th city, Egypt, using HVSR and seismic techniques

Adel M.E. Mohamed a,b,*, H.E. Abdel Hafiez a, M.A. Taha a

a National Research Institute of Astronomy and Geophysics (NRIAG), Egypt
b Earthquake Monitoring Center (EMC), Sultan Qaboos University (SQU), Sultanate of Oman

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Abstract  The damage caused by earthquake occurrences in different localities necessitates the evaluation of the subsurface structure. A priori estimation of the site effects became a major challenge for an efficient mitigation of the seismic risk. In the case of moderate to large earthquakes, at some distances from large events, severe damage often occurred at zones of unfavorable geotechnical conditions that give rise to significant site effects. The damage distribution in the near-source area is also significantly affected by fault geometry and rupture history. The microtremor (background noises) and shallow seismic surveys (through both the seismic refraction and Multi-channel Analysis of Surface Waves (MASW)) were carried out in a specific area (The club of October 6 city and its adjacent space area). The natural periods derived from the HVSR (Horizontal to Vertical Spectral Ratio) analysis vary from 0.37 to 0.56 s. The shallow seismic refraction data, which were conducted at the area, are used to determine the attenuation of P-waves ($Q_p$) in different layers, using the pulse-width technique. The evaluation of the site response at the studied area yields amplification factor of the ground motion, ranging between 2.4 and 4.4.

1. Introduction

The damage to human infra-structures and the disturbances of the local life affairs represent an inestimable cost for the national and local authorities, usually requiring international cooperation. Most of the crowded cities and high populated areas (as Cairo City) are located on soft sediments (valleys, estuaries, recent deposits, etc.), the soil structure of which is prone to amplify seismic waves (Murphy and Shah 1988; Bard 1994). This phenomenon is usually called site effect or site amplification, since the amplitude of the motion highly...
depends upon the local properties of the soil. The site response (transfer function) is evaluated through the geotechnical parameters (layer thicknesses, densities, boreholes). The P-wave velocities are obtained from the shallow seismic refraction survey (Mohamed, 2003, 2009; Mohamed et al., 2008) and the S-wave velocities are deduced from the Multi-channel Analysis of Surface Waves (MASW) survey.

The investments necessary for conventional techniques, i.e. boreholes, are prohibitive for developing countries and for regions of a moderate seismic activity. One of the most important and commonly encountered problems in geotechnical earthquake engineering is the evaluation of ground response. Moreover, it is commonly known that, during earthquakes, the damage to structures is reasonably associated with the underlying subsoil conditions. So, the dynamic properties of the underlying soils are greatly reflected by the characteristics of earthquake ground motions at the ground surface (i.e., ground response). It has, also, been demonstrated that, the geographic distribution of the ground shaking-related damage and its intensity are strongly dependent on the local lithological and physical properties (e.g., silt and clay content, as well as void ratio) and conditions (depth-to-water table and base ment relief) of the near-surface sediments (Minakami and Sakuma, 1948; Kanai, 1952; Ooba, 1957; Mueller et al., 1982).

Consequently, understanding of the soil effect on the propagated seismic wave became an urgent need, in order to map areas, where amplification is likely and conveying this information to emergency managers and community officials. Moreover, it can be used in land-use planning, reducing business vulnerability, retrofitting building, producing guidelines for new constructions and assisting in infrastructure upgrading. Therefore, over the years, a great effort has been done in the level of theory (e.g., Ohsaki, 1981; Kramer, 1996) and level of application (e.g., Faeh et al., 1993, 1994; Panza et al., 1996).

The Horizontal to Vertical Spectral Ratio (HVSR) technique (Nakamura, 1989) for the noise survey (microtremor) is now widely used to estimate the site effect parameters (fundamental frequency and mostly the associated soil amplification), in which many surveys using this technique have provided convincing results (see Bard, 1999, for a review). However, a general agreement of a methodology for the data acquisition, data processing and results interpretation has yet to be found. The current study considers the study of the reliability of a low-cost method, based on the measurement of ambient vibrations. The focus was put on the so-called HVSR (Horizontal-to-Vertical Spectral Ratio), which became widely used after the work of Nakamura (1989).

The objective of this research is to estimate the fundamental frequencies (natural periods) at the 6th of October club area and its extension (Fig. 1), where a part of the area is occupied by a swimming pool, playground and some gardens. The rest of the area is still empty. The obtained parameters; such as the fundamental frequency, will be integrated with the previous calculated geotechnical information (Mohamed et al., 2012), in order to evaluate the site response and the seismic hazard, which will be valuable for designing and constructing the space area.

2. Geologic Setting

The surface geology in and around the studied area (Fig. 2) reveals that, the oldest rocks are the Upper Cretaceous rocks, represented by Bahariya Formation, Abu Roash Formation and Khoman Formation. Then, the Tertiary rocks are represented by the Upper Eocene (Maadi Formation), the Oligocene rocks (Gebel Qatrani Formation and the Basalt flows), the Lower Miocene (Gebel Khashab Formation), the Pliocene (undifferentiated Pliocene deposits) and the Quaternary deposits (Nile sediments). All the investigated sites are occupied by Gebel Qatrani Formation. This formation is represented by a sequence of continental to littoral marine alternating clastics, burrowed siltstone, and reddish claystone (as derived from the surface geological map and the drilled boreholes). In general, the surface sediments in the studied area are loose to very loose
3. Methodology

3.1. HVSR Method

The microtremors are caused by the daily human activities; such as the movements of machinery in factories, motor cars and people walking; and the natural phenomena, such as the flow of water in rivers, rain, wind, variation of atmospheric pressure and the oceanic waves. However, microtremors are now not regarded as nuisance “noises”, but rather a useful “signal”. In this sense, they are sometimes referred to as “uncontrolled signals”. Nakamura (1989) proposed the basis of qualitative arguments that, the Horizontal-to-Vertical Spectral Ratio (HVSR) is a reliable estimation of the site response to the S-wave, providing reliable estimates, not only for the resonance frequency, but also for the corresponding amplification. These ratios are much more stable than the noise spectra and that, on soft soil sites; they exhibit a clear peak, which is well correlated with the fundamental resonance frequency. HVSR data from the ambient noise recordings imply both reliability of the results and rapidity of the data collection.

The interested area, which covers an area of about 1.3 km², is classified into grid with cell dimensions of 315 × 240 m (as shown in Fig. 3) where R1 represents the first row (SW–NE) and C1 represents the first column (SE–NW), in the grid. So, each site location is represented by a row number and a column number (e.g. R1C1) and there is an additional site located at the top of hill exposure.

Fig. 2 The Geological map of the interested area (modified after Conco Coral, 1987).

Fig. 3 Classification of the studied area into grid with dimensions 315 × 240 m.
Henstridge, 1984). The noise energy depends upon the source locations and upon the impedance contrast between the rocky basement and the overlying soft sediments (Chouet et al., 1998). The main hypothesis for using the ambient vibration is that, they are dominantly composed of surface waves, which allow the dispersion property to be used (Tokimatsu, 1997).

The microtremor measurements were done at 25 site locations (continuous measurements for at least two hours at each site) at the studied area with the following precautions, according to Duval (1994), Nakamura (1996), Mohamed (2003) and Bard (2007) and SESAME project guidelines:

(1) Carrying out measurements, using 1 s (or higher) tri-axial velocity-meter, for the analysis at periods longer than 1 s.

(2) Avoid long external wiring, which may bring into mechanical and electronic interferences.

(3) Avoid measurements in windy or rainy days. Wind causes large and unstable distortions at low frequencies.

(4) Avoid recordings close to roads with heavy vehicles, which cause strong and rather long transients.

The Taurus Portable Seismograph is used as a data logger, which incorporates a three-channel 24-bit Digitizer, GPS receiver and System Clock, removable data storage, and remote communication options. Taurus is configurable locally, using the color display screen. The used three-component seismometer in the current study is Trillium Compact 120s, that provides the convenience and ease of installation, low noise and high clip level.

![Fig. 4 The microtremor work sheet record of site R1C1.](image-url)
Fig. 4 represents the field work sheet of the site R1C1 and all the recording data are listed in Table 1, while Fig. 5 illustrates a representative example of the recorded data.

The raw data were processed using the J-SESAME software developed within the European project (SESAME, 2004). For each site the microtremor record is corrected for the base-line effect to guarantee the stationary assumption validity. Various numbers of windows, with 25 non-overlapping second (2500 samples) duration, were selected among the quietest part of the recorded signals (for each site, 10 windows at least were used). This is done using the STA/LTA anti-trigger algorithm. This time window is sufficiently long to provide stable results in the studied range of frequency. The time series was tapered with a 10% cosine taper for avoiding leakage and an amplitude spectrum is computed using the Fast Fourier Transform (FFT) for all the three components. A bandwidth coefficient value of 40 is used in the current analyses. The smoothing of the spectra of each component is a mandatory analysis operation. In fact, as shown by several authors (e.g., Bindi et al., 2000; Picozzi et al., 2005), it allows the stabilization of the H/V curves, avoiding the presence of spurious peak, due to the seismic or instrumental or numerical noises. Then, the two horizontal components were merged together using a geometrical mean option, as:

\[ H = \left( |x_t y_t| \right)^{0.5} \]  

Table 1  The recorded microtremor records at the area of interest.

| SN | Site | Coordinate (degree) | Instruments | Microtremor |
|----|------|---------------------|-------------|-------------|
|    |      | Latitude | Longitude | Data logger | Sensor (s) | Date   | Duration (min) |
| 1  | R1C1 | 29.980444 | 30.949976 | Taurus | T.C. 120 | 17/5/2012 | 128 |
| 2  | R1C2 | 29.982037 | 30.952385 | Taurus | T.C. 120 | 17/5/2012 | 120 |
| 3  | R2C1 | 29.981924 | 30.948599 | Taurus | T.C. 120 | 17/5/2012 | 130 |
| 4  | R2C2 | 29.983839 | 30.951237 | Taurus | T.C. 120 | 17/5/2012 | 104 |
| 5  | R3C1 | 29.983606 | 30.947184 | Taurus | T.C. 120 | 17/5/2012 | 122 |
| 6  | R3C2 | 29.985443 | 30.949909 | Taurus | T.C. 120 | 17/5/2012 | 143 |
| 7  | R4C1 | 29.985455 | 30.945648 | Taurus | T.C. 120 | 17/5/2012 | 129 |
| 8  | R4C2 | 29.987314 | 30.948359 | Taurus | T.C. 120 | 17/5/2012 | 121 |
| 9  | R4C3 | 29.989201 | 30.951111 | Taurus | T.C. 120 | 17/5/2012 | 121 |
| 10 | R4C4 | 29.990997 | 30.953754 | Taurus | T.C. 120 | 15/5/2012 | 119 |
| 11 | R4C5 | 29.992786 | 30.956419 | Taurus | T.C. 120 | 15/5/2012 | 122 |
| 12 | R4C6 | 29.994585 | 30.959097 | Taurus | T.C. 120 | 15/5/2012 | 122 |
| 13 | R5C1 | 29.987234 | 30.944109 | Taurus | T.C. 120 | 16/5/2012 | 125 |
| 14 | R5C2 | 29.989082 | 30.946901 | Taurus | T.C. 120 | 16/5/2012 | 135 |
| 15 | R5C3 | 29.990881 | 30.949614 | Taurus | T.C. 120 | 16/5/2012 | 130 |
| 16 | R5C4 | 29.992636 | 30.952240 | Taurus | T.C. 120 | 15/5/2012 | 111 |
| 17 | R5C5 | 29.994307 | 30.954760 | Taurus | T.C. 120 | 15/5/2012 | 122 |
| 18 | R5C6 | 29.995979 | 30.957283 | Taurus | T.C. 120 | 15/5/2012 | 124 |
| 19 | R6C1 | 29.988955 | 30.942619 | Taurus | T.C. 120 | 16/5/2012 | 153 |
| 20 | R6C2 | 29.990818 | 30.945463 | Taurus | T.C. 120 | 16/5/2012 | 138 |
| 21 | R6C3 | 29.992556 | 30.948126 | Taurus | T.C. 120 | 16/5/2012 | 126 |
| 22 | R6C4 | 29.994263 | 30.950735 | Taurus | T.C. 120 | 15/5/2012 | 104 |
| 23 | R6C5 | 29.995815 | 30.953104 | Taurus | T.C. 120 | 16/5/2012 | 118 |
| 24 | R6C6 | 29.997366 | 30.955482 | Taurus | T.C. 120 | 15/5/2012 | 120 |
| 25 | T.P. | 29.992590 | 30.953820 | Taurus | T.C. 120 | 18/5/2012 | 134 |

T.C.: Trillium compact 120s.
where: $H$ is the horizontal component computed by geometrical mean, $x_f$ is the modulus of spectra of the N–S component, and $y_f$ is the modulus of spectra of the E–W component. The horizontal FFT spectra of the 25 s data subsets were divided

Fig. 6  Panel 1 represents the amplitude spectrum of the three components of the site R1C1, Panel 2 shows the horizontal spectrum rotation with azimuth degrees, Panel 3 demonstrates the H/V spectral ratio curve (amplification at the fundamental frequency), Panel 4 illustrates the H/V rotation with azimuth degrees, and Panels 5 and 6 show the damping test for the peak amplitude at frequency 1.58 Hz which is of industrial origin and at frequency 2.06 which is of natural origin.
by the vertical ones yielding a number of H/V's curves for each site. These H/V's are then averaged and the standard deviations at each frequency of interest are calculated. The resonance frequency and the corresponding amplitude at each site could then be determined. Finally, each peak is checked, if it is of natural or industrial origin, as shown later. Fig. 6 shows an example of such calculation sequence.

The presence of strong sources acting during the recordings may be revealed also by means of a directional analysis of the H/V curves. In order to perform such analysis, the horizontal components of motions are rotated in the 0°-180° degree range and are combined for the H/V computation at regular intervals. This is very useful to check whether a site is 1-D. Like the rotated H/V, J-SESAME computes the spectra with horizontal components spanning different azimuths. The azimuth is regularly counted clockwise from the north. This is useful to check the direction of energy release. The rotated spectra and the rotated H/V curves are conducted for all the sites of interest.

### 3.2. Broadening of the First-Pulse (Pulse-Width)

The shallow seismic refraction survey was carried out through applying the forward, inline, midpoint and reverse shootings to create the compressional waves (P-waves). Amplitudes of the seismic waves are not only controlled by the geometrical spreading or focusing, but also by the reflection and transmission coefficients, that occur at the discontinuities. Besides this, the wave amplitudes may be reduced, because of the energy loss due to inelastic material behavior or internal friction during the wave propagation. These effects are called intrinsic attenuation. Also, the scattering of energy at small-scale heterogeneities along the travel paths may reduce the amplitudes of seismic waves. In the case of such scattering attenuation, however, the integrated energy in the total wave-field remains constant, while the intrinsic attenuation results in a loss of mechanical wave energy (e.g., by transformation into heat). The wave attenuation is usually expressed in terms of the dimensionless quality factor Q.

Gladwin and Stacey (1974) applied for the P-waves an empirical relation, that relates the pulse duration of the P-waves, the source and the travel path of a seismic wave:

\[ \tau_{1/2} = \tau_o + (CT/Q_p) \]  

where \( \tau_{1/2} \) is the P-wave pulse duration at a distance \( d \) from the source; \( \tau_o \) is the P-wave pulse duration at the source (at zero distance); \( C \) is a constant; \( T \) is the P-wave travel time; \( Q_p \) is the quality factor for P-wave.

The pulse duration is defined as the linear extrapolation of the maximum slope of the beginning of the pulse before the first onset (using the base-line, as a reference) and the first zero after the maximum of the pulse (Liu et al., 1994). The above mentioned equation is valid for homogeneous media. Wu and Lees (1996) have proved that, this equation can be applied to the fractured media. Jongmans (1991) found that, this method is not valid, when the hypocentral distances are less than 1.2 times the wave length. Gladwin and Stacey (1974) determined the value of the constant \( c \) to be equal to 0.5 (for the P-waves).

Applying the pulse-width attenuation relation, the P-wave attenuation for each layer at all sites is determined for the requirement of site effect estimation (Figs. 7 and 8).

The local attenuation \( Q_s \) for the horizontal shear waves (SH-waves) of the sedimentary column is roughly specified by the following empirical relations of Brocher (2008), due to the absence of such relations for the considered area and the severe lack in records required for achieving such relations:

\[ Q_s = -16 + 104.13 \text{SH} - 25.225 \text{SH}^2 + 9.2184 \text{SH}^3 \]  

(for: \( 0.3 \text{ km/s} < \text{SH} \) (horizontal shear wave velocity) \( < 5.0 \text{ km/s} \)).

\[ Q_s = 13 \]  

(for \( \text{SH} < 0.3 \text{ km/s} \))

### 3.3. Site Response

One of the most important and commonly encountered problems in the geotechnical earthquake engineering is the evaluation of ground response. Moreover, it is commonly known that, during earthquakes, the damage to structures is reasonably associated with the underlying subsoil conditions. So, the dynamic properties of the underlying soils are greatly reflected by the characteristics of earthquake ground motions at the ground surface (i.e., ground response). It has also been demonstrated that, the geographic distribution of ground shaking-related damage and its intensity are strongly dependent on the local lithological and physical properties (e.g., silt...
and clay content, as well as void ratio) and conditions (depth-to-water table and basement) of the near-surface sediments (Minakami and Sakuma, 1948; Kanai, 1952; Ooba, 1957; Mueller et al., 1982). This would cause upsurge of groundwater carrying sand, silt and clay in the sedimentary parts of unconsolidated, pours, water-saturated and has a shallow water table (i.e., liquefaction). This is due to the fact that, the stress in such conditions reduces the shear resistance capacity of the soils.

Consequently, understanding the soil effect on the seismic wave became an urgent need, in order to map areas, where amplification is likely and conveying this information to emergency managers and community officials. Moreover, it can be used in land-use planning, reducing business vulnerability, retrofitting building, producing guidelines for new constructions and assisting in infrastructure upgrade. Therefore, over the years, a great effort has been done in the level of theory (e.g., Ohsaki, 1981; Kramer, 1996) and application (e.g., Faeh et al., 1990, 1993, 1994; Zahradnik et al., 1991, 1994; Panza et al., 1996), in order to interpret the earthquake motion characteristics at a site. Both the theory and application are often grouped; according to the dimensionality of the problems they can address (Kramer, 1996).

After addressing the importance of ground response issue, an attempt was made to predict ground surface motions (taking into account the effect of local soil conditions), using the one-dimensional ground response analysis approach. This relies on the theoretical model proposed by Kramer (1996). He stated that, the ground motion at any layer can be easily computed from the ground motion at any other layer (e.g. input motion imposed at the bottom of the soil column), using the transfer function \( T_j(x) \), relating the displacement amplitude at layer \( i \) to that at layer \( j \), as given by:

\[
F_{ij}(x) = \frac{|u_i|}{|u_j|} = \frac{A_i(x) + B_i(x)}{A_j(x) + B_j(x)}
\]

Because of harmonic motion, the acceleration and velocity can be derived from the displacement (i.e., \( \ddot{u} = \omega \dot{u} = \omega^2 u \)), Eq. (5) also describes the amplification of acceleration and velocities from layer \( i \) to layer \( j \). This equation indicates that, the motion in any layer can be determined from the motion at any other layer. Hence, if the motion at any point in the soil profile is known, the motion at any other point can be contributed and predicted.

4. Results

4.1. HVSR

The results obtained from the microtremor measurements, that were conducted at 25 sites in the study area (which covered by the 6th of October club), using the HVSR technique, demonstrate the fundamental (resonance) frequency \( f_o \) of the soft sedimentary cover in the study area. There are peaks of industrial origin in the frequency range (1.1–1.65) affecting most of the sites, as shown through Fig. 9 and listed in Table 2. These peaks are attributed to the effect of the main electric power of the wider area.

It is also noted that, the fundamental frequency \( f_o \) of less than 2 Hz covers the southern part (the area occupied by the gardens and the swimming pool) at the sites R1C2, R2C1, R2C2, R3C1 and R3C2. Values of \( f_i \) of less than 2 Hz are located also at the western site (R6C1) and the northeastern part, covering the sites R5C5, R6C5 and R6C6. The low values of \( f_o \) (< 2 Hz) at the mentioned sites are attributed to the considerable thickness of the soft sediment section overlying the bedrock. The low values of \( f_o \) are compatible with the surface geology, since the studied area is covered by surface sediments of loose to very loose sands, silts, gravels, clays and rock fragment materials.

It is straightforward to identify the following general characteristics of the investigated area, as shown in Fig. 9:

- Most of the area is dominated by low resonant frequency range (1.49–2.68 Hz), which is in consistency with the general geology of the area, indicating that most of the area has a considerable sedimentary section.
Fig. 9  HVSR curves of the site R1C1, R1C2 R3C1, R3C2, R4C1, R4C2, R4C3, R4C4, R4C5, R4C6, R5C1, R5C2, R5C3, R5C4, R5C5, R5C6, R6C1, R6C2, R6C3, R6C4, R6C5, R6C6.

9.1: HVSR Curves of the site R1C1.
9.2: HVSR Curves of the site R1C2.
9.3: HVSR Curves of the site R2C1.
9.4: HVSR Curves of the site R2C2.
9.5: HVSR Curves of the site R3C1.
9.6: HVSR Curves of the site R3C2.
9.7: HVSR Curves of the site R4C1.
9.8: HVSR Curves of the site R4C2.
9.9: HVSR Curves of the site R4C3.
9.10: HVSR Curves of the site R4C4.
The low resonant frequency ($f_o < 2$ Hz) is concentrated mainly at the northeastern, southern and western parts of the investigated area.

The middle part is characterized by $f_o \geq 2$ Hz, which reflects the decreasing of the soft sediment thickness.

4.2. Site Response

A detailed geotechnical model of the October 6 club area was developed using the existing geotechnical data, gathered from the available borehole data and complemented with the
Mohamed et al. (2013) studied the soil section, in terms of P- and S-wave velocities, using the shallow seismic refraction and MASW techniques. The shear wave velocity is the best indicator of the sediment stiffness (Bullen, 1963; Aki and Richards, 1980), therefore it is recognized, as a key factor for the site response of the soft soil (Borcherdt, 1970).

The amplification of ground motion is proportional to \(1/(V_s \rho)^{0.5}\), where \(V_s\) is the shear wave velocity and \(\rho\) is the density of the investigated soil (Aki and Richards, 1980). Since the change in density is relatively small with depth, the \(V_s\) value can be used to represent the site conditions. Therefore, the shear wave velocities of the soil columns are used in the current study to define the amplification characteristics at the selected 24 sites.

As discussed by Mohamed et al. (2013), the S-wave velocity is derived by inverting the dispersive phase velocity of the surface Rayleigh wave, utilizing the Multi-channel Analysis of Surface Waves (MASW) technique (Park et al., 1999; Miller et al., 1999; Xia et al., 2000). The seismic refraction was carried out through applying the forward, inline, mid-point and reverse acquisition system to create the compressional waves (P-waves). The P-waves are acquired by generating seismic energy using a sledge hammer of 8 kgm, sending the created seismic waves inside the earth. The direct and refracted waves are detected through 40 Hz vertical geophones. The surveyed 24 profiles have 94 m long spread. The geophones, which were firmly coupled to the ground, had 2 m fixed geophone spacing. The technique is to shoot the profile (5 shots) at 5 m distance from both ends, mid-point, in addition to 2 inline shots (between G12-13 and G36-37).

The obtained P- and S-wave velocities and the deduced depth model at the interested area, in addition to the available borehole data, are used to evaluate the ground motion amplification versus frequency. The results demonstrate the amplification-frequency curves, as shown in Fig. 10 and listed in Table 3, where the \(f_{30}\) is in the range of 3.4 to \(>20\) Hz (down to 30 m depth) and the corresponding ground motion amplification factor is in the range of 1.69–4.74.

The fundamental (resonance) frequency down to 30 m depth \(f_{30}\) distribution map at the interested area (Fig. 11) shows that, the \(f_{30}\) varies within a short distance, this could be done due to the undulations of the bedrock surface, causing variations in the soil thickness. The soil type also changes from place to place. In the northeastern part of the area, the near-surface bedrock or rocky outcrops are present, while the recent alluvium with variable thickness, with recent or sub-recent clays and silts are present in the southwestern
### Table 2  The Fundamental frequency obtained from the HVSR curve.

| SITE   | Coordinates (degree) | Windows | Frequency $F_o$ | Amplitude $A_o$ | Remarks |
|--------|-----------------------|---------|-----------------|-----------------|---------|
| Code   | Latitude              | Longitude | WL(s) | No | ± STD  | ± STD  |         |
| R1C1   | 29.9804440            | 30.9499759 | 40    | 80 | 1.58   | 0.13   | 4.31    | 0.55   | Industrial |
| R1C2   | 29.9820366            | 30.95238495 | 40     | 91 | 1.61   | 0.02   | 6.55    | 0.80   | Industrial |
| R2C1   | 29.9819241            | 30.94859886 | 40    | 86 | 1.6     | 0.03   | 7.44    | 0.99   | Industrial |
| R2C2   | 29.9838390            | 30.95123672 | 40    | 23 | 1.12    | 0.17   | 2.49    | 0.36   | Industrial |
| R3C1   | 29.9836063            | 30.94718361 | 40    | 65 | 1.64    | 0.14   | 4.21    | 0.52   | Industrial |
| R3C2   | 29.9854431            | 30.94990921 | 40    | 119 | 1.91    | 3.38   | 3.38    | 0.43   | Natural |
| R4C1   | 29.9854546            | 30.94564819 | 40    | 59 | 2.06    | 0.12   | 3.66    | 0.57   | Natural |
| R4C2   | 29.9873142            | 30.94835854 | 40    | 99 | 1.1     | 0.21   | 3.78    | 0.89   | Natural |
| R4C3   | 29.9892006            | 30.95111084 | 40    | 56 | 2.21    | 0.23   | 2.52    | 0.41   | Natural |
| R4C4   | 29.9909973            | 30.95375443 | 40    | 45 | 1.22    | 0.16   | 2.87    | 0.47   | Natural |
| R4C5   | 29.9927864            | 30.95641899 | 40    | 57 | 1.53    | 0.15   | 2.55    | 0.41   | Industrial |
| R4C6   | 29.9945850            | 30.95909691 | 40    | 31 | 2.38    | 0.24   | 2.98    | 0.63   | Industrial |
| R5C1   | 29.9872341            | 30.94410896 | 40    | 52 | 2.29    | 0.28   | 3.25    | 0.58   | Industrial |
| R5C2   | 29.9890823            | 30.94690132 | 40    | 74 | 2.68    | 0.31   | 3.18    | 0.46   | Industrial |
| R5C3   | 29.9908810            | 30.94613573 | 40    | 128 | 2.43    | 0.31   | 3.22    | 0.6   | Industrial |
| R5C4   | 29.9926337            | 30.95223999 | 40    | 50 | 1.91    | 0.16   | 3.24    | 0.59   | Industrial |
| R5C5   | 29.9943066            | 30.95475960 | 40    | 33 | 1.5     | 0.14   | 4.81    | 1.51   | Industrial |
| R5C6   | 29.9959793            | 30.95728302 | 40    | 75 | 1.55    | 0.27   | 3.51    | 0.61   | Industrial |
| R6C1   | 29.9889545            | 30.94261932 | 40    | 73 | 2.43    | 0.27   | 2.84    | 0.45   | Industrial |
| R6C2   | 29.9908180            | 30.94546318 | 40    | 78 | 2.16    | 0.31   | 2.78    | 0.49   | Industrial |
| R6C3   | 29.9925556            | 30.94812584 | 40    | 74 | 2.15    | 0.31   | 2.73    | 0.63   | Matural |
| R6C4   | 29.9942527            | 30.95073509 | 40    | 57 | 2.04    | 0.22   | 2.52    | 0.55   | Natural |
| R6C5   | 29.9958153            | 30.95310402 | 40    | 70 | 1.49    | 0.15   | 4.82    | 1.48   | Natural |
| R6C6   | 29.9973600            | 30.95548248 | 40    | 64 | 1.49    | 0.15   | 3.59    | 0.54   | Industrial |
| Blatup | 29.9973660            | 30.95548248 | 40    | 96 | 1.56    | 0.15   | 5.04    | 1.24   | Industrial |
| East-Blat | 29.9973660  | 30.95548248 | 40    | 68 | 1.51    | 0.17   | 5.08    | 0.91   | Industrial |
| West-Blat | 29.9973660       | 30.95548248 | 40    | 76 | 1.49    | 0.17   | 4.36    | 0.79   | Natural |

**Estimating the near-surface site response to mitigate earthquake disasters at the October 6th**
Analyzing the resulting distribution maps of $f_{o30}$ and the corresponding amplification factor ($A_{o30}$) (Figs. 11 and 12), it is straightforward to identify the following general characteristics of the investigated area:

- The $f_{o30}$ at the northeastern part, which is in consistency with the general geologic features, indicates that the area has a thin sedimentary cover or outcropping bedrock, with higher frequency values (from 12 to $>20$ Hz).
The results at the southern part are characterized by lower values of $f_{o30}$ (from 3.4 to 7 Hz), where the thickness of the soft soil is considerably large.

The occupied part of low $f_{o30}$ is characterized by the presence of swelled clay.

The amplification factors are evaluated at the sites of interest at various frequencies; 0.25, 0.5, 1.0, 1.25, 1.5, 2.0, 3.0, 3.0, 5.0 and 10.0 Hz, respectively, as listed in Table 3. The amplification factors at the different frequencies are used for the microzonation. The microzonation, based amplification
factor at the investigated sites, demonstrates (Fig. 13): the amplification rating map at frequency 3 Hz (upper left panel), the amplification rating map at frequency 5 Hz (upper right panel), the amplification rating map at frequency 10 Hz (lower left panel) and the amplification rating map at the fundamental frequency (lower right panel).

Fig. 10 (continued)
## Table 3
Site effect (amplification at the fundamental frequency and at various frequencies) at 24 sites.

| SN | CODE | Easting | Northing | VS30 | Site response (up to 30 m depth) | Amplification at frequency |
|----|------|---------|----------|------|----------------------------------|---------------------------|
|    |      |         |          |      |                                  | 0.25 Hz | 0.5 Hz | 1.0 Hz | 1.25 Hz | 1.50 Hz | 2.0 Hz | 3.0 Hz | 5.0 Hz | 10.0 Hz |
| 1  | R1C1 | 696828  | 3151089  | 318  | D                                | 11.1     | 3.36   | 1.01   | 1.01   | 1.02   | 1.02   | 1.03   | 1.05   | 1.11   | 1.33   | 3.10   |
| 2  | R1C2 | 697048  | 3145636  | 371  | C                                | 10.7     | 3.13   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.03   | 1.05   | 1.12   | 1.34   | 3.04   |
| 3  | R2C1 | 695334  | 3155030  | 380  | C                                | 5.2      | 2.53   | 1.00   | 1.01   | 1.04   | 1.07   | 1.10   | 1.18   | 1.47   | 2.52   | 1.03   |
| 4  | R2C2 | 696967  | 3155391  | 400  | C                                | 4.1      | 4.47   | 1.01   | 1.02   | 1.09   | 1.14   | 1.22   | 1.43   | 2.41   | 3.12   | 1.70   |
| 5  | R3C1 | 695435  | 3149133  | 653  | C                                | 3.4      | 2.03   | 1.00   | 1.00   | 1.02   | 1.09   | 1.14   | 1.21   | 1.40   | 1.94   | 3.11   | 1.22   |
| 6  | R3C2 | 696407  | 3149034  | 379  | C                                | 4.8      | 1.91   | 1.00   | 1.01   | 1.05   | 1.08   | 1.12   | 1.21   | 1.50   | 1.91   | 1.18   |
| 7  | R4C1 | 699088  | 3149156  | 363  | C                                | 14.6     | 4.74   | 1.00   | 1.00   | 1.01   | 1.01   | 1.01   | 1.03   | 1.06   | 1.17   | 2.02   |
| 8  | R4C2 | 694784  | 3147125  | 781  | B                                | 6.2      | 2.97   | 1.00   | 1.01   | 1.03   | 1.05   | 1.08   | 1.14   | 1.36   | 2.38   | 1.58   |
| 9  | R4C3 | 696523  | 3147153  | 405  | C                                | 10.5     | 2.03   | 1.00   | 1.00   | 1.01   | 1.02   | 1.02   | 1.04   | 1.10   | 1.30   | 2.02   |
| 10 | R4C4 | 699036  | 3147116  | 327  | D                                | 19.2     | 1.69   | 1.00   | 1.00   | 1.00   | 1.00   | 1.00   | 1.00   | 1.02   | 1.06   | 1.24   |
| 11 | R4C5 | 694495  | 3145176  | 549  | C                                | 14.5     | 2.41   | 1.00   | 1.00   | 1.00   | 1.00   | 1.00   | 1.00   | 1.05   | 1.15   | 1.74   |
| 12 | R4C6 | 698970  | 3145151  | 463  | C                                | 9.7      | 2.48   | 1.00   | 1.00   | 1.01   | 1.02   | 1.03   | 1.05   | 1.12   | 1.38   | 2.47   |
| 13 | R5C1 | 694538  | 3143056  | 456  | C                                | 12.2     | 4.01   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.03   | 1.08   | 1.25   | 2.78   |
| 14 | R5C2 | 696439  | 3143120  | 426  | C                                | 12.4     | 2.08   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.03   | 1.06   | 1.18   | 1.83   |
| 15 | R5C3 | 699090  | 3142880  | 289  | D                                | 12.1     | 2.52   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.03   | 1.07   | 1.22   | 2.17   |
| 16 | R5C4 | 695215  | 3149976  | 1262 | B                                | 8.6      | 3.62   | 1.00   | 1.00   | 1.02   | 1.03   | 1.04   | 1.08   | 1.18   | 1.62   | 3.01   |
| 17 | R5C5 | 695976  | 3150089  | 482  | C                                | 8.6      | 3.62   | 1.00   | 1.00   | 1.02   | 1.03   | 1.04   | 1.08   | 1.18   | 1.62   | 3.02   |
| 18 | R5C6 | 697108  | 3150129  | 335  | D                                | 12.7     | 2.30   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.03   | 1.06   | 1.19   | 1.96   |
| 19 | R6C1 | 698074  | 3150066  | 390  | C                                | 13.1     | 2.70   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.03   | 1.07   | 1.20   | 2.09   |
| 20 | R6C2 | 699005  | 3150176  | 366  | C                                | 13.3     | 2.78   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.03   | 1.06   | 1.19   | 2.04   |
| 21 | R6C3 | 695005  | 3150930  | 576  | C                                | 10.2     | 4.19   | 1.00   | 1.00   | 1.01   | 1.02   | 1.03   | 1.05   | 1.13   | 1.41   | 4.17   |
| 22 | R6C4 | 696326  | 3151078  | 388  | C                                | 16.0     | 2.64   | 1.00   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.04   | 1.12   | 1.61   |
| 23 | R6C5 | 698028  | 3151031  | 438  | C                                | 16.0     | 2.64   | 1.00   | 1.00   | 1.00   | 1.00   | 1.01   | 1.01   | 1.02   | 1.06   | 1.29   |
| 24 | R6C6 | 698984  | 3151039  | 349  | C                                | 10.9     | 4.69   | 1.00   | 1.00   | 1.01   | 1.02   | 1.02   | 1.05   | 1.11   | 1.33   | 4.07   |
Fig. 11  The fundamental frequency distribution map at the interested area.

Fig. 12  The amplification at the corresponding fundamental frequency distribution map at the interested area.
5. Discussion and Conclusions

Most of the cities and high populated areas (as Cairo City) are located on soft sediments (valleys, estuaries, recent deposits, ...), the soil structures of which are prone to amplify seismic waves. This phenomenon is usually called site effect or site amplification, since the amplitude of the motion highly depends upon the local properties of the soil. Consequently, the risk mitigation requires fine investigations of each geologic setting. The investments necessary with conventional techniques, i.e. boreholes are prohibitive for developing countries and for regions with moderate seismic activities.

The microtremor survey was conducted at 24 sites in the area, which covered the 6th of October club. The results obtained from the HVSR demonstrate the fundamental (resonance) frequency ($f_0$) of the soft sedimentary cover in the study area. According to the reliability of the HVSR curves, there are peaks of industrial origin in the frequency range (1.1–1.65 Hz) affecting most of the measured sites. These peaks are attributed to the effect of the main electric power. It is also noted that, the fundamental frequencies ($f_0$) of values less than 2 Hz cover the southern part (the area occupied by the gardens and swimming pool). $f_0$ is less than 2 Hz at the western site (R6C1) and the northeastern part. The low values of $f_0$ (<2 Hz) at the mentioned sites are attributed to the considerable thickness of the sedimentary cover. The low values of $f_0$ are found to be compatible with the surface geology.

The deduced amplification-frequency curves at the 24 sites of the studied area, demonstrating a fundamental frequency down to 30 m depth ($f_{0,30}$), are in the range of 3.4 to >20 Hz. The results reflect that; $f_{0,30}$ at the northeastern part indicates a thin sedimentary cover or outcropping bedrock.
with higher values (12 to > 20 Hz). The southern part is characterized by lower values of fundamental frequencies (3.4–7 Hz), where the thickness of the soft soil is relatively large. The low fundamental frequency area is characterized by the presence of swelled clay, and the corresponding ground motion amplifications factors are in the range of 1.69–4.74. The amplifications at the various frequencies (0.25, 0.5, 1.0, 1.25, 1.5, 2.0, 3.0, 5.0 and 10.0 Hz) are evaluated.

The microzonations, based amplification factor at frequencies 3, 5, 10 and 30 Hz, are evaluated, where the zones of amplification are classified into low (1–2), moderate (2–3) and high (> 3).

The obtained 30 values (due to the upper 30 m) are higher than those obtained from the HVSR. This is due to the depth variation, where the f30 values deduced from HVSR are due to a considerable large depth.

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