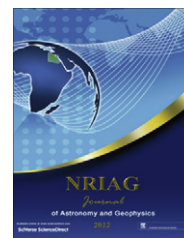National Research Institute of Astronomy and Geophysics

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Engineering seismological studies in and around Zagazig city, Sharkia, Egypt

M. El-Eraki [a], A.A. Mohamed [b], A.A. El-Kenawy [a], M.S. Toni [b], I.M. Shimaa [a,*]

[a] *Zagazig University, Faculty of Science, Geology Department, Zagazig, Egypt*
[b] *National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Egypt*

Abstract The aim of this paper is to study the ground vibrations using Nakamura technique to evaluate the relation between the ground conditions and the earthquake characteristics. Microtremor measurements were carried out at 55 sites in and around Zagazig city. The signals were processed using horizontal to vertical spectral ratio (HVSR) technique to estimate the fundamental frequencies of the soil deposits and its corresponding H/V amplitude. Seismic measurements were acquired at nine sites for recording the surface waves. The recorded waveforms were processed using the multi-channel analysis of surface waves (MASW) method to infer the shear wave velocity profile. The obtained fundamental frequencies were found to be ranging from 0.7 to 1.7 Hz and the maximum H/V amplitude reached 6.4. These results together with the average shear wave velocity in the surface layers were used for the estimation of the thickness of the upper most soft cover layers (depth to bedrock). The sediment thickness generally increases at the northeastern and southwestern parts of the area which is in good agreement with the local geological structure. The results of this work showed the zones of higher potential damage in the event of an earthquake in the study area.

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Introduction

Zagazig city is the capital of El Sharkia governorate and situated on the Nile Delta in the midst of a fertile district. It is located on the Muweis Canal and presents a promising area for

both agricultural expansion and urban development. The importance of Zagazig city is referred to its high density of population, urbanization, and its archaeological sites as the ruins of Bubastis which located 3 km southeast of the town. The study area (Fig. 1) is located between latitudes 30°32′45″ and 30°38′24″N and longitudes 31°25′26″ and 31°33′36″E.

It is well known and widely accepted that site effects play an important role in characterizing seismic ground motions because they may strongly amplify seismic motions within the uppermost layer of the ground (Abd El-Aal, 2008, 2010a,b). The ground shaking site effect caused by an earthquake can vary significantly even within a small distance. This is because at sites having soft sediments or topographic undulation, the ground motion is amplified as the seismic energy gets trapped

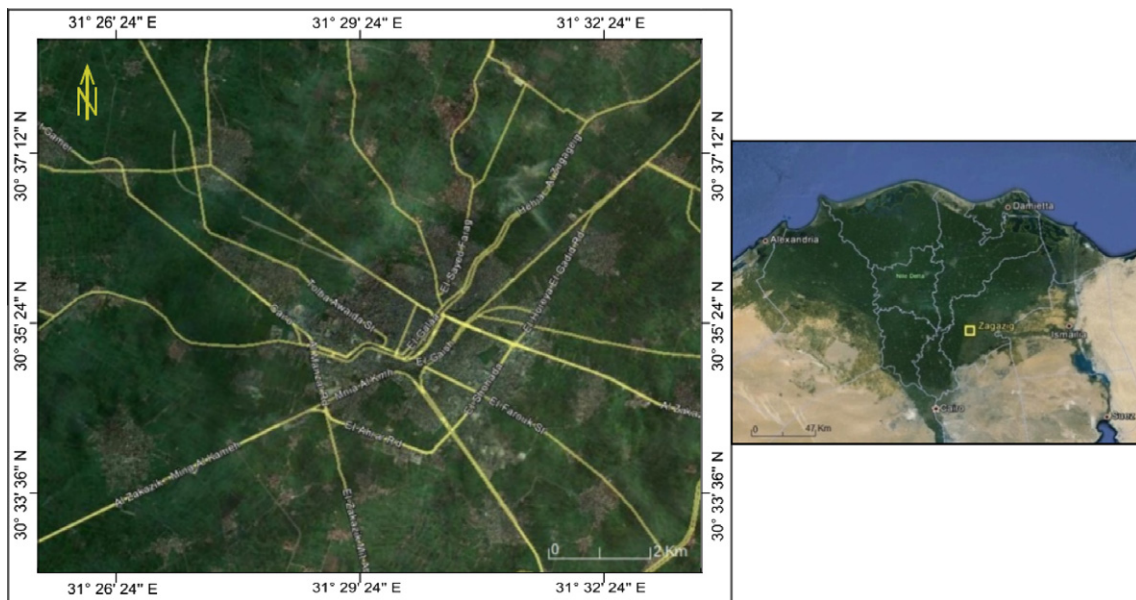ELSEVIER | **Production and hosting by Elsevier**

Fig. 1   Location map of the study area.

due to the impedance contrast between sediments and the underlying bedrock leading to a resonance patterns (Lacave et al., 1999). Theoretical analysis and observational data have shown that each site has a specific resonance frequency at which ground motion gets amplified (Bard, 2000). Manmade structures having resonance frequency matching that of the site have the maximum likelihood of getting damaged. Therefore, studying of site response of the study area is important in urban planning and construction of the seismically-safe structures.

The surface of the earth is always in motion at seismic frequencies, even without earthquakes. These constant vibrations called microtremors and characterized by very small amplitude. Generally, these ambient vibrations are generated by natural disturbances such as wind, rain and ocean waves and by human activities such as people walking, motor cars and movement of machinery in factories (Okada, 1997). The horizontal to vertical (H/V) spectral ratio method, also called the Nakamura technique (Nakamura, 1989) is characterized by its simplicity, low-cost both for survey and analysis and minimal disturbances to the other activities especially in the inhabitant areas. The H/V technique is effective in estimating the fundamental frequency of soil deposits while it gives the lower bound estimate of the H/V amplitude of ground vibration.

Surface wave measurements were carried out in the area of study as it has a great potential for site characterization. Surface waves were generated by the active source means that seismic energy is intentionally generated at a specific location relative to the geophone spread and recording begins when the source energy is imparted into the ground. Surface wave energy decays exponentially with depth beneath the surface. Longer wavelength (longer period and lower frequency) surface waves travel deeper and thus give more information about deeper velocity structure. Shorter wavelength (shorter period and higher frequency) surface waves travel shallower and thus give more information about shallower velocity structure (SeisImager/SW™ Manual, 2006). The surface waves were processed using the 1-D multi-channel analysis of surface waves (MASW) method to infer the shear wave velocity profile through two main steps; the first is the calculation of the dispersion curves, the second is the inversion of the dispersion curves to a shear wave velocity profile. The shear wave velocity is very important in studying the vibration characteristics of subsurface layers which are important for the earthquakes resistant structure design (Kanai, 1983). The results of average shear wave velocity together with the microtremor results were used for estimating the thickness of sediments overlying the bedrock.

Geology

The eastern part of the Nile Delta is characterized by low relief and its surface slopes gently towards the north direction and take a rolled shape towards the south direction where the land rises up to a moderately elevated plateau with elevation ranges between 5 and 100 m (Bayoumy, 1971; Abd El Gawad, 1997). El Sharkia governorate (Fig. 2) is mainly composed of Nile silt, Neonile deposits, Pre-Nile deposits, stabilized dunes, sabkha deposits and marsh, silt, clay and evaporates (GPC and CONOCO, 1987). Based on information from boreholes drilled in Zagazig city by Sharkia Portable Water and Sanitation Co. and gathered from the educational buildings authority (drilled by Faculty of Engineering, Cairo University and Faculty of Petroleum Engineering, Suez Canal University), the study area consists of two layers: clay and thick deposits of sands graded from very fine to coarse grained sand with clayey and shale intercalations at some depths. El Sharkia governorate geomorphologically has its own bearing groundwater resources, reservoirs and discharging drainage canals.

The stratigraphic succession of El Sharkia governorate is ranging in age from Tertiary to Quaternary and has a thickness of more than 500 m with Mid-Tertiary basaltic flows. The Quaternary deposits cover most of the governorate

Fig. 2   Geological map of the study area (GPC and CONOCO, 1987).

particularly in the north and northeast directions. It consists of loose quartizitic gravels, sands and clay cap bed and some mud lenses. Its eastern part is represented by old deltaic plains of fluviatile deposits and characterized by a moderately low relief (Geological survey of Egypt, 1971). The superficial geologic conditions show reducing thickness of the clay cap in many localities in El Sharkia governorate as a result of the presence of sand islets and shallow buried sand Geziras. These superficial sands represent easy arid rapid infiltration (El Gamili et al., 1990).
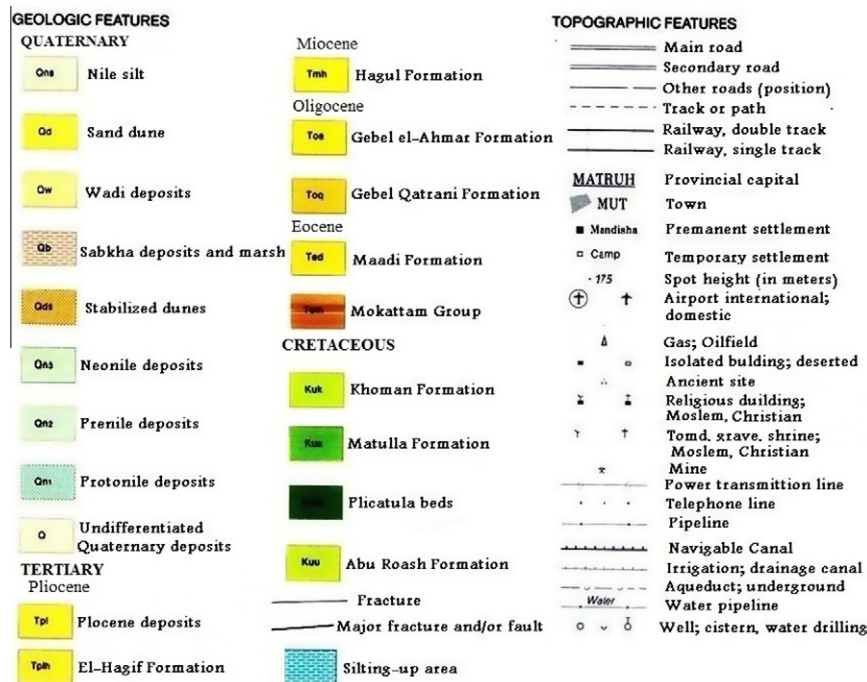
GEOLOGIC FEATURES

QUATERNARY

Qns	Nile silt
Qd	Sand dune
Qw	Wadi deposits
Qb	Sabkha deposits and marsh
Qds	Stabilized dunes
Qn3	Neonile deposits
Qn2	Prenile deposits
Qn1	Protonile deposits
Q	Undifferentiated Quaternary deposits

TERTIARY
Pliocene

Tpl	Pliocene deposits
Tplh	El–Hagif Formation

Miocene

Tmh	Hagul Formation

Oligocene

Toe	Gebel el–Ahmar Formation
Toq	Gebel Qatrani Formation

Eocene

Ted	Maadi Formation
Tem	Mokattam Group

CRETACEOUS

Kuk	Khoman Formation
Kum	Matulla Formation
	Plicatula beds
Kuu	Abu Roash Formation

Fracture

Major fracture and/or fault

Silting–up area

TOPOGRAPHIC FEATURES

Main road
Secondary road
Other roads (position)
Track or path
Railway, double track
Railway, single track

MATRUH — Provincial capital
MUT — Town
Mandisha — Premanent settlement
Camp — Temporary settlement
·175 — Spot height (in meters)
Airport international; domestic
Gas; Oilfield
Isolated bulding; deserted
Ancient site
Religious building; Moslem, Christian
Tomd. grave, shrine; Moslem, Christian
Mine
Power transmittion line
Telephone line
Pipeline
Navigable Canal
Irrigation; drainage canal
Aqueduct; underground
Water — Water pipeline
Well; cistern, water drilling

Fig. 2   (*continued*)

The subsurface Tertiary rocks are divided from bottom to top into: Oligocene rocks, Miocene rocks and Pliocene rocks. The subsurface Miocene rocks are subdivided from down to top into Sidi Salem, Qawasim and Rosetta formations. While the Pliocene rock units are subdivided from bottom to top into Abu Madi, Kafr EI Sheikh and Wastani formations (Schlumberger, 1984).

Seismicity

The seismicity of the study area is related to the interaction between the African, Arabian and Eurasian plates and Sinai subplate. The area was affected by earthquakes both historical (e.g. 2200 BC, Sharkia province earthquake with maximum intensity VII near Tell Basta and Abu Hammad) and instrumental (e.g. 29 April, 1974, Abu-Hammad earthquake with magnitude = 4.9). Zagazig city is located in a moderately active seismic area and is affected by six active seismogenic zones which have different levels of seismic activity as follows:

(1) *Abu Zabal Zone*, where the epicenter of 28 December, 1999 earthquake and its aftershocks were occurred. The epicentral area was affected by three normal faults trending in the E–W, NW–SE, and NE–SW directions. The structure in the Abu Zabal area was created by tensional stresses (Abd El-Aal, 2010b).

(2) *South-West Cairo Zone (Dahshour zone)*, where the epicentral area of the 12 October, 1992 earthquake (M_w = 5.8) took place. This zone is affected by two faults trending in E–W and NW–SE directions (Meshref, 1990).

(3) *Cairo-Suez District Zone (CSD)* which is characterized by moderate seismic activity. The focal mechanism solution for the 29 April, 1974, Abu Hammed earthquake gave two fault planes trending in ENE–WSW and

NNW–SSE directions with left lateral strike slip motion along the second plane (Mousa, 1989; Hassib, 1990).

(4) *Gulf of Suez Zone*, the structure of the Gulf of Suez rift is dominated by normal faults linked by transverse active faults have N–S and NNE–SSW trends (Colleta et al., 1988). The southern end of the Gulf is characterized by relatively high seismic activity due to tensile stresses resulting from the crustal movements among the Arabian, African plates and the Sinai subplate (Shwartz and Arden, 1960). The southern Gulf of Suez zone is characterized by higher seismic activity when compared with the northern and central zones of the gulf and the 1969 and 1972 earthquake swarms were reported at this zone.

(5) *Gulf of Aqaba Zone (AQB)*, which is characterized by a high seismic activity. Its structure is dominated by N–S strike slip system that resulted in the creation of en-echelon rhomb shaped grabens where changes in the trend to NNW–SSE and back to N–S occur. These grabens are filled with a few kilometers of sediment (Dahy, 2010). The importance of the Gulf of Aqaba comes from the occurrence of earthquake swarms (e.g. 1983, 1993 and 2002 earthquake swarms).

(6) *South-East Mediterranean Sea Zone (Med)*, which is characterized by the occurrences of small and moderate to large earthquakes. Its high level of seismic activity is related to the continental shelf and the probable deep faults (Maamoun and Ibrahim, 1978).

Microtremor data acquisition and processing

Microtremor measurements were carried out at 55 sites (Fig. 3) in Zagazig area during two periods; the first period was from 16 to 23 June, 2011 and the second from 22 to 27 February,
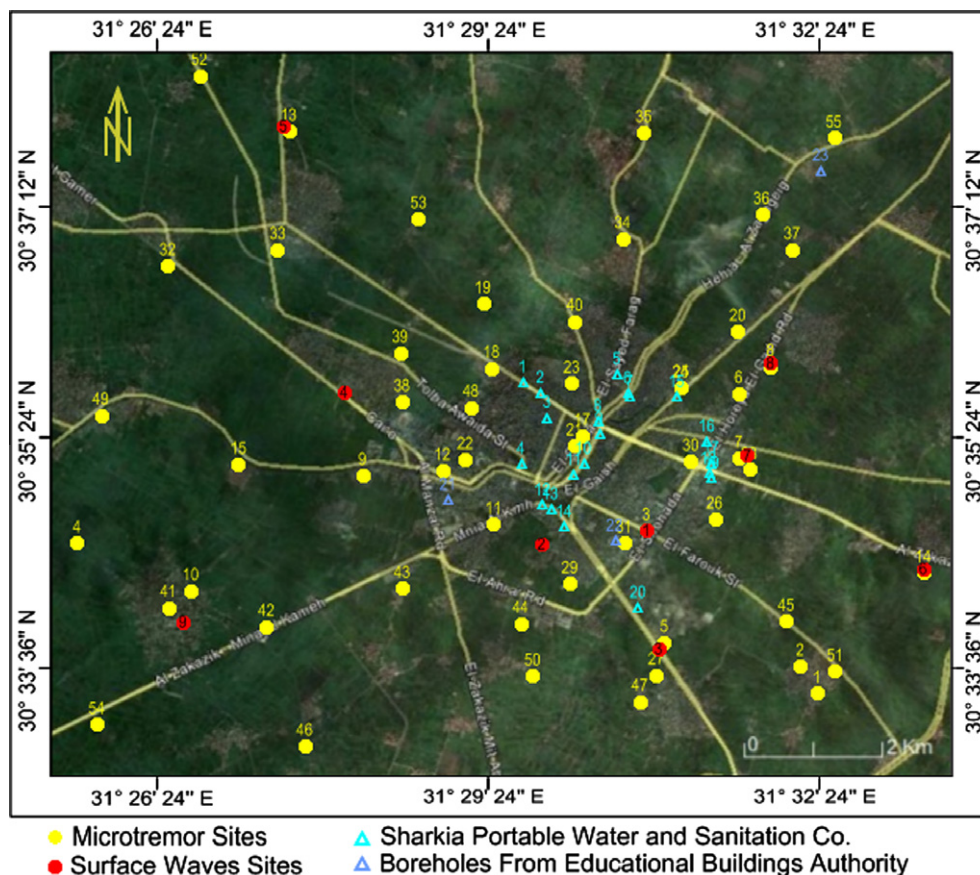
Fig. 3 The location of boreholes, microtremor and surface waves measuring sites.

2012. The measurements were acquired using high sensitivity seismometers of compact Trillium-120 s equipped with three components digital seismograph data logger (Taurus instrument model of NANOMETRICS) during daytime. The ambient vibrations were recorded continuously for a duration ranging from 22 min to 1 h 30 min at each recording site with sampling rate of 200 Hz for the most of the sites and 100 and 250 Hz for 16 sites. At each site, the sensor was oriented to the north direction and vertically leveled with good coupling with the ground. The data were acquired, processed and interpreted according to the SESAME Project guidelines and precautions (SESAME Project, 2004).

Microtremor data were processed using Geopsy software (Geophysical Signal Database for Noise Array Processing) version 2.7.4 (geopsypack-2.4.3). The window length selected for computing the H/V spectral ratio was ranging from 25 to 50 s depending on the noise level stability and the frequency of interest at each site. Hence, the number of stable windows was varying from site to another but always $\geqslant 10$. Then, a cosine taper of 5% was applied on the signal; Fourier spectra were calculated for the three components (NS, EW and Z components) and smoothed using Konno–Ohmachi algorithm with a smoothing constant ranging from 30 to 50. The resulting spectral amplitudes of horizontal components were averaged by the squared average and divided by the vertical spectra to calculate the H/V Spectral ratio for each individual window. Then, the average H/V spectral ratio was computed and the standard deviation of the spectral ratio estimated. The data processed with sampling frequency from 0.3 to 15 Hz for all the sites.

The reliability of the H/V curves was tested throughout the following criteria:

(1) The fundamental frequency f_0 should be greater than $10/$ window length ($f_0 > 10/l_w$ and this means that, for a peak to be significant at the frequency of interest, at least 10 significant cycles in each window should be present.
(2) Large number of windows and cycles is needed: the total number of significant cycles: $n_c = l_w n_w f_0$ should be larger than 200, where n_w is the number of windows selected for the average H/V curve.
(3) An acceptably low level of scattering between all windows is needed. Large standard deviation values ($\sigma_A(f)$) mean that ambient vibrations are strongly nonstationary and undergo some kind of perturbations, which may significantly affect the physical meaning of the H/V peak frequency.

Therefore, it is recommended that $\sigma_A(f)$ be less than a factor of 2 (for $f_0 > 0.5$ Hz), or a factor of 3 (for $f_0 < 0.5$ Hz), over a frequency range at least equal to $[0.5f_0, 2f_0]$ (SESAME Project, 2004). Sites 42, 44 and 45 were found to be unreliable and excluded from the results.

As the measurements were made in an urban environment, the H/V peaks were tested to check for the industrial origin such as man-made noise. Sites 23, 24, 26, 38, 41 and 47 were found to be of industrial origin and discarded from the results. Also, at some sites the H/V peak showed an industrial origin and excluded from the results, and the second peak of natural origin
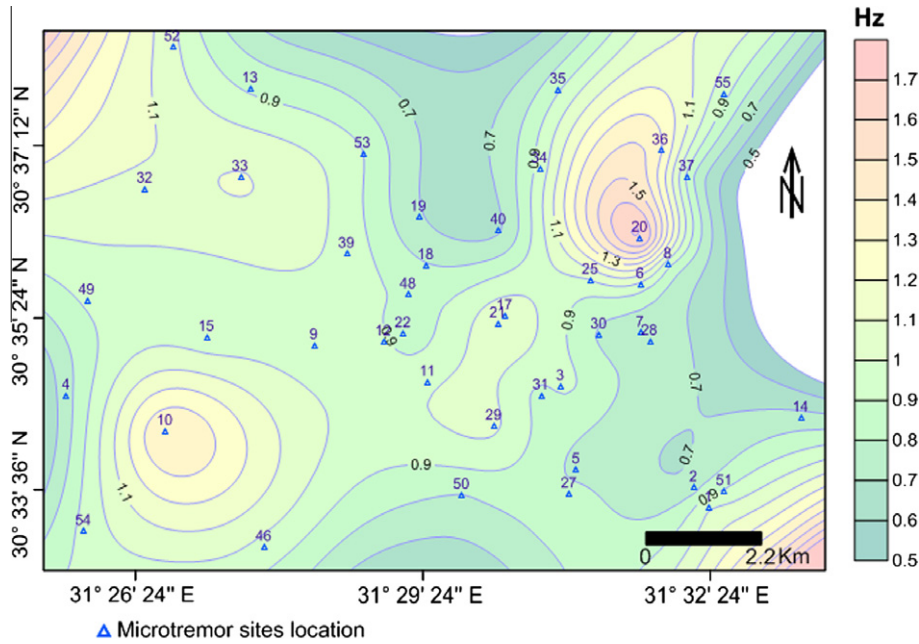
Fig. 4 Contour map of the fundamental resonance frequencies.

was taken instead. Finally, the peak frequency of site number 43 was excluded from the results because of the bad acquisition.

The resulted values of fundamental frequency (f_0) and the corresponding H/V amplitude (A_0) at every site were estimated and contour maps were made to show the variation in f_0 and A_0 values (Figs. 4 and 5). The values of f_0 are increasing at the northeastern side reaching a maximum value of 1.7 Hz and towards the southwestern side reaching maximum value of 1.4 Hz and decreasing at the central part of the study area. Parolai et al. (2001) stated that, the resonance frequency becomes lower in areas where the basement depth is greater and higher where it is shallower. Accordingly, the presence of higher and lower values reflects the variation in the thick-

nesses of sediments through the area. The values of A_0 are increasing at the eastern and central parts of the area indicating that at these parts the ground shaking is likely to be amplified than the rest of the study area. It should be pointed that the H/V spectral ratio technique is very effective in determining the fundamental frequency at the measuring site, but it gives the lower bound estimates of the H/V amplitude at that site (Abdel-Rahman et al., 2010). The f_0 values are ranging from 0.7 to 1.7 Hz while A_0 values reached to $\approx$6.4. The low values of f_0 reflect the thick section of soft sediments (clay, shale, silt, fine to coarse grain sand) in the area of study.

The presence of clear peak of H/V curve (Fig. 6) is an indicative to the impedance contrast between the uppermost surface
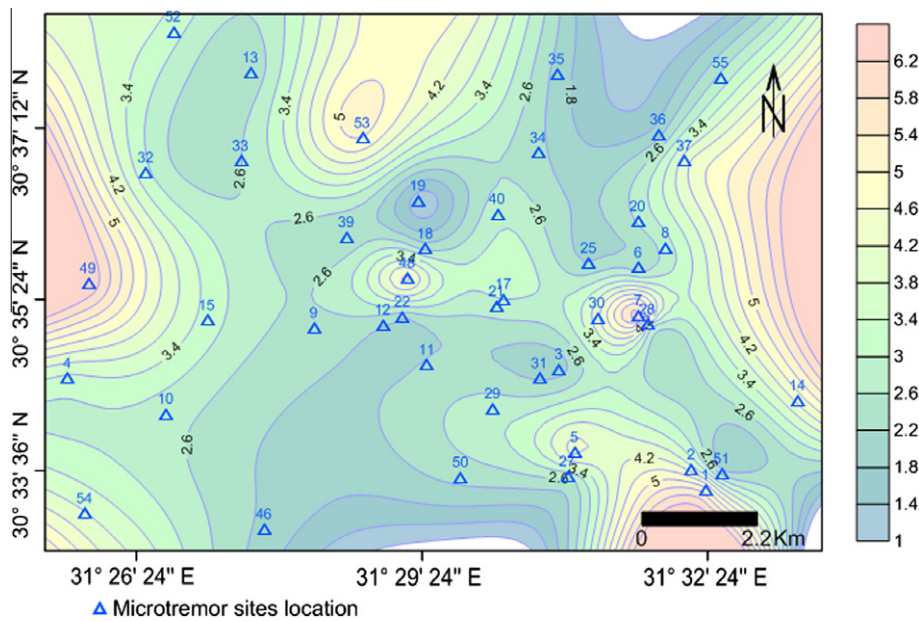

Fig. 5 Contour map of the H/V amplitude.

soil and the underlying hard rock, where higher values of A_0 are associated with sharp velocity contrasts (Bard and SES-AME Team, 2004) and is likely to amplify the ground motion. The unclear low frequency peaks with moderate impedance contrast indicate that the site under the measurement point is characterized by thick and stiff sedimentary deposits. The presence of two peaks reflects the presence of two large impedance contrasts at that site at two different scales: one for a thick structure and the other one for a shallow structure.

Surface waves data acquisition and processing

The measurements of surface waves were carried out at nine sites (Fig. 3) in the study area during the period from 17 to 19 June, 2011. The data were collected using the 48 channels Strata View (SLAVE, GEOMETRICS) seismograph. Only 24 channels were used in the measurement with 4.5 Hz vertical geophones. The spread was linear with normal shooting (1 D MASW) and the geophone spacing was 1 m and the total length of the spread was 23 m. The first five sites were recorded with two normal shootings, the first one was at offset interval from the first geophone equal to 10 m and the second was at 5 m while the four other site had the normal shooting at offset distance equal to 5 m only. A sledgehammer struck against metallic plate was used to generate the seismic wave energy since it is low cost and easily repeatable. The shot point at each site was stacked to enhance the arrivals at distant geophones and to increase the signal to noise ratio at all the geophones.

The software programs Surface Wave Analysis Wizard (Pickwin, version 3.3.0.3) and WaveEq (Surface Wave Analysis, version 2.2.0.3) from the SeisImager software package were used for the processing of the measured data. The processing includes two main steps described as follows: the first step is to calculate the dispersion, or change in phase velocity with frequency using Pickwin module. Surface wave dispersion can be significant in the presence of velocity layering, which is common in the near-surface environment (SeisImager/SW™ Manual, 2006). The next step is to calculate the shear wave velocity (V_s) profile by mathematical inversion (based on the least square method) of the dispersive phase velocity of surface waves using WaveEq module.

The results of shear wave velocity (V_s) profiles (Fig. 7) show low shear wave velocities. In the given examples the V_s curve consists of four layers having shear wave velocities equal to 112, 113, 171 and 249 m/s and depths of 1.4, 3.8 and 7.2 m with the fourth layer not reached to its lower surface at site number 1. While at site number 9 the V_s velocities are 116, 130, 147 and 181 m/s with corresponding depths equal to 1.4, 3.8 and 7.2 m with the fourth layer not reached to its lower boundary. These results agree with the borehole data which indicate that the subsurface is consists of clay layer at the surface change laterally to shale layer at other localities underlying on very fine grain sand graded to coarse grain with depth and some intercalations of clay and silt at some depths.

The average thirty meter shear wave velocity (AVS) as defined by IBC was calculated at each site and used to determine the site classification from the UBC (Building Seismic Safety Council, 1997; International Code Council, 2000 and 2003; Underwood and Hayashi, 2005). The sites were found to be classified as class D ($180 < $ UBC V_s $30 \leqslant 360$ m/s) which means that the soil under these sites is stiff soil. However, only

sites number 6, 8 and 9 were found to be classified as class E (UBC V_s $30 < 180$ m/s) which means that the soil under these sites is soft soil.

Fig. 8 shows the P wave velocity (V_p) corresponding to the S wave velocity at each layer. The program calculates the P wave velocity from the following formula (SeisImager/SW™ Manual, 2006):

$$V_p = 1.11 V_s + 1290 \quad m/s$$

The values of P wave velocities at each layer from top to bottom are: 1381, 1423.2, 1444.3 and 1527.5 m/s. These values are well correlated with the slandered V_p values of clay ($V_p = 1100–2500$ m/s) and water saturated sand ($V_p = 1200–1900$ m/s) (after Bonner and Schock, 1981). This is also comparable with the borehole data which refer that the subsurface succession is generally composed of clay and sand with surface ground water level ranging from 4.2 to 8.1 m throughout the study area.

Sediment thickness in relation with H/V ratio

The relationship between the shear wave velocity V_s structure and the fundamental resonance frequency obtained from H/V processing have been studied by several authors (Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2002; Motamed et al., 2007). It has been recently demonstrated that the thickness can be determined directly from the frequency determined from H/V spectral ratio of ambient noise or microtremors (Yamanaka et al., 1994; Field, 1996). In this study, the values of the fundamental resonance frequency resulted from microtremor measurements were used with the results of the average shear wave velocity for the first 30 m in sediments obtained from the surface wave measurements close to it in the following formula (Bard, 2000) to compute the sediment thickness:

$$F = \frac{V_{av}}{4H}$$

where H is the thickness (m) of sediments overlying the half-space, V_{av} is the average shear wave velocity (m/s) for the first 30 m in sediments and f is the fundamental resonance frequency (Hz) of soil deposits. The results show that the thickness increases at the northeastern and southwestern parts reaching maximum value of 65.7 m and decreases at the central part of the study area.

These results show a good agreement with the microtremor and surface wave results. As at the areas where the fundamental frequency of soil deposits increase the thickness is found to be decrease and vice versa demonstrating the inverse relationship between the frequency and the thickness of sediments. The results of thickness are correlated with the depth of coarse grained sand layer at the boreholes. The above formula is simple suggesting that the environment is consisted of a soft soil layer lies on a rigid substratum and the shear wave velocity is homogenous within the study area. Also, the mechanical properties of the soil can cause some intrinsic uncertainty in the thickness data (Delgado et al., 2000) implies that these results should be taken as general guidelines only.

Summary and conclusion

Zagazig city is located on the Nile Delta in the midst of a fertile district and was affected by a number of earthquakes both his-
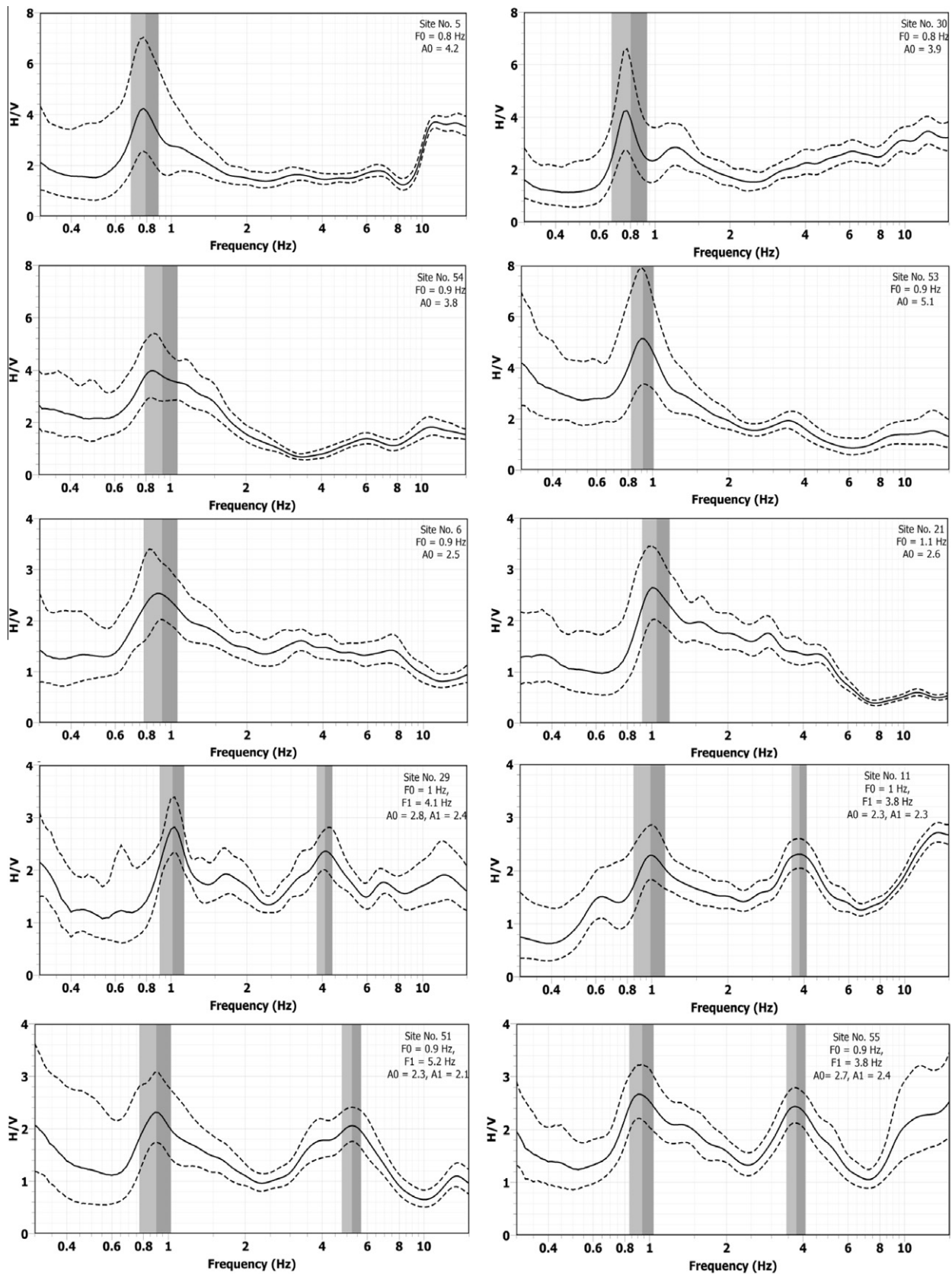
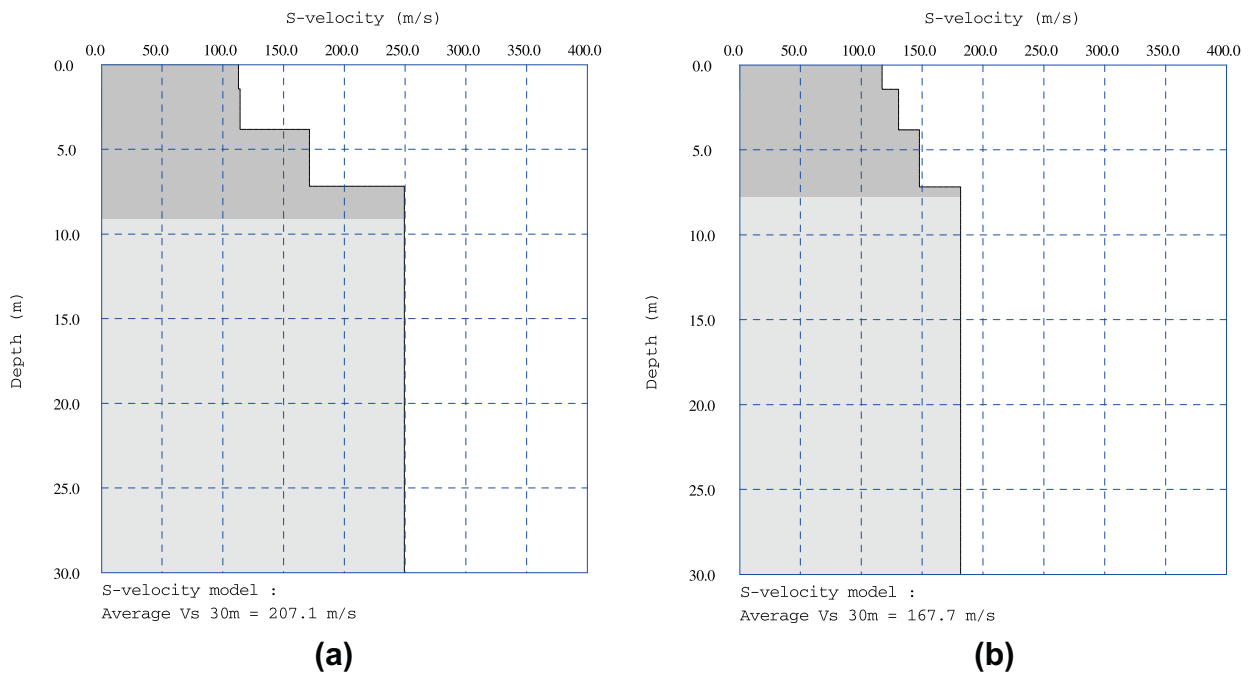**Fig. 6**   Examples of H/V peak frequencies at the measured sites.

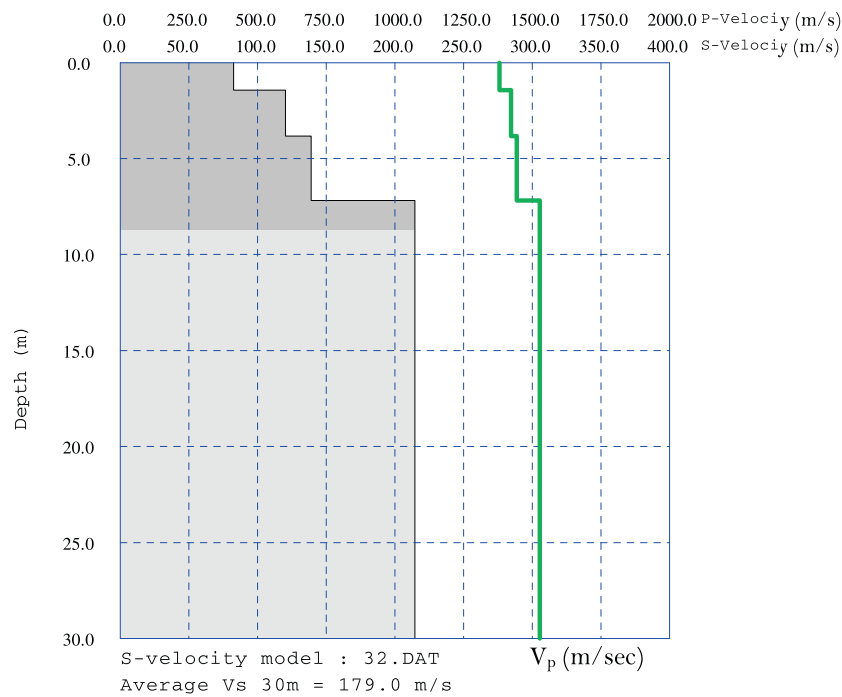**Fig. 7** Examples from V_s profiles, (a) for site No. 1 and (b) for site No. 9.

Fig. 8 An example from V_s profile at site No. 8.

torically and instrumentally. The low values of f_0 reflect the thick section of soft sediments in the study area. The high impedance contrast between the uppermost surface soil and the underlying hard rock is represented by the high values of A_0 indicating that at these sites the ground motion is likely to be amplified in the case of an earthquake. The unclear low frequency peaks indicate that the soil at these sites is thick and stiff which comes in agreement with the results of the analysis of the surface wave measurements where the site classification was determined from the average shear wave velocity by the Uniform Building Code (UBC). The site classification showed that most of the study area lies on stiff soil (class D)

while other regions lies on soft soil (class E). The calculated longitudinal wave (V_p) values also come in agreement with the values of the sediments constituting the study area.

The results of microtremor and surface waves are highly comparable with the borehole data. The relationship between the fundamental frequency of the soil deposits and the average shear wave velocity gave a reasonable estimation of the sediment thickness. Microtremor is powerful tool in microzonation studies due to the low cost, speed and ease of data acquisition and analysis. The results of this study should be considered before the construction of civil engineering structure in the study area.

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