INTRODUCTION

Clear evidence of seismic damage due to local geology was first observed in Japan, during the 1923 Kanto earthquake. Several recent earthquakes (e.g., Michoacan, Mexico, 1985; Dahshore, Egypt, 1992; Northridge, U.S.A., 1994; Kobe, Japan, 1995, and Athens, Greece, 1999) clearly indicate that understanding local site effects is one of the major challenges of seismic risk mitigation. Several techniques are employed to compute the site response for soft deposits (i.e., resonance frequencies and amplification factor). Measuring microtremors based on the analysis of ambient noise has been regarded as one of the preferred approaches in estimating site responses, particularly in highly populated urbanized areas because the data collection is portable and non-invasive and the data analysis is straightforward and easy to do. This method measures the spectral ratio of the horizontal to vertical ($H/V$) component of ambient noise. The prominent peak of the spectral amplitude ratio corresponds to the fundamental frequency of the site under investigation (Nogoshi and Igarashi 1971; Nakamura 1989). Many researchers have studied the reliability of this method (e.g., Duval et al. 1995; Field and Jacob 1995; Teves-Costa et al. 1996; Lachet et al. 1996; Bour et al. 1998; Bindi et al. 2000; LeBrun et al. 2001) and concluded that the ambient noise $H/V$ spectral ratios provide reliable estimates of the fundamental frequencies of soil deposits.

Our study is concerned with the Nile delta, which at present covers an onshore area of about 25,000 km$^2$ and an equal offshore area extending to the 200-m isobath (Schlumberger 1984, 1987). The southern apex of the delta is at 30°N, approximately 30 km north of Cairo, where the Nile River splits into the eastern branch (Damietta) and the western branch (Rosetta). The Nile delta is a rapidly growing population center and consists of Miocene-Quaternary age sediments. The potential seismic risk of the Nile delta, even if it is located on the zone of moderate seismic activity, is due to the amplification of the ground motion caused by the presence of thick basin sediments. The area recently suffered extensive damage and casualties due to an M 5.9 earthquake located 25 km southwest of Cairo in 1992. The biggest losses were in Cairo and the Nile delta basin. Several thousand people were killed or injured and thousands of buildings collapsed. Liquefaction was detected in many places at and around the epicentral area.

The main goal of this paper is to investigate the effects of the Nile delta basin configuration on the incoming seismic waves by estimating the fundamental frequency and site response at several sites within the basin. Because of the lack of seismic observations in the basin and its urbanized nature, we used the $H/V$ spectral ratio of the ambient noise approach to achieve this goal. We collected microtremor observations at 120 sites located along three parallel north-south profiles. We then applied the $H/V$ spectrum ratio technique to estimate the predominant frequencies and site effects at all sites. We developed fundamental frequency and $H/V$ amplitude maps and compared these with the geologic structures beneath the basin.

GEOLOGY OF THE NILE DELTA

The Nile delta basin has long been subjected to comprehensive geological studies, especially in the northern zone where oil companies have collected exploratory deep borehole data. The delta is a lobate build-up whose formation begun in Miocene times. The ancient distributors (branches) disappeared due to intensive irrigation and construction in the onshore delta plain and eventually reduced to two main branches, the Damietta (eastern branch) and the Rosetta (western branch).

The Nile River has passed through five main episodes since the valley was cut down in late Miocene time (Said 1981). These five episodes of the river were termed the Eonile (Late Miocene), Paleonile (Late Pliocene), Protonile (Early Pleistocene), Preenile (Middle Pleistocene), and Neonile (Late Pleistocene-Holocene). The deposits of each of these rivers are distinct in lithology, stratigraphic relationships, and mineral content.
Geomorphically, the Nile delta basin has been studied by many authors (e.g., Attia 1954; Butzer 1958; Shata 1966; El-Fayoumi 1968; Shata and El-Fayoumi 1970; Abou Al-Izz 1971; and Zaghloul et al. 1989), who all concluded that the basin is surrounded on its southeastern and southwestern borders by two structural Eocene limestone tablelands and two deltaic plains. The modern plain comprises the main portion of the fertile and cultivated land of the Nile delta. The Nile delta basin is characterized by relief, and the regional slope is toward the north (4 m/km). Figure 1 shows the geologic map of the Nile delta while Figure 2 shows the cross-section of the profile AA'.

The composite columnar section of the subsurface deposits of the Nile delta proposed by Rizzini et al. (1978) is shown in Figure 3. This deposit section is composed mainly of Sidi Salim, Qawasim, Rosetta (Miocene), Abou Madi formations, Kafer El-Sheikh, El-Wastani, and Mit Ghamer formations (Pliocene-Pleistocene cycle), and Bilqas formation (Holocene cycle) at the top. The Holocene Bilqas formation is a coastal lagoonal deposit made up of silts and sandy mud constituting the agricultural soil of the delta. It represents the cap sediments overlying the Mit Ghamer formation, which is the main aquifer in the Nile delta. The Abou Madi formation, composed of interbedded sands and shale, is the gas producing horizon in the Nile delta.

**MICROTREMOR MEASUREMENTS**

We carried out ambient noise measurements in the Nile delta basin during May 2005 at 120 sites as shown in Figure 1. The weather was generally calm with no strong winds or rain. The measurements were done using two broadband seismological stations individually on three parallel profiles that covered the basin from south to north at an interval spacing of 2 km. Each station was equipped with a hand-held Taurus portable data acquisition system with excellent-quality data with 24-bit resolution, a dynamic range > 140 dB at 100 sps, and precise GPS timing; and a Trillium 240 broadband velocity seismometer. The Trillium 240 is an exceptional, very broadband low-noise seismometer ideally suited to portable and fixed network applications. The Trillium 240 has a response flat to velocity from 240 seconds to 35 Hz and a self-noise below the New Low Noise Model (NLNM) from 100 s to 10 Hz. The Trillium 240 has a response flat to velocity from 240 seconds to 35 Hz and a self-noise below the New Low Noise Model (NLNM) from 100 s to 10 Hz. The Trillium 240 has an internal, fully automatic mass re-centering capability, which facilitates both local and remote recentering. Trillium seismometers have a symmetric triaxial arrangement of the sensing elements. The use of three identical axis elements ensures the same frequency response for vertical and horizontal outputs, is less susceptible to rapid changes in temperature, and guarantees true orthogonality of the three outputs. The precise global positioning system (GPS) was used for recording the coordinates of the observation sites. We followed the guidelines proposed by Koller et al. (2004) to ensure reliable experimental conditions in terms of recording parameters, recording duration, measurement spacing, in-situ soil-sensor coupling, artificial soil-sensor coupling, sensor setting, nearby structures, weather conditions, and disturbances.

The recording time for each site is 30 m after the mass centering done with sampling frequency 100 Hz. For each site, the data were segmented into number of segments not less than 10 segments of equal duration. Underground structures and heavy traffic roads were avoided.
The $H/V$ ratio (the ratio between the Fourier spectra of the horizontal and vertical components of ambient noise) has been explored by several Japanese scientists (Nogoshi and Igarashi 1971; Shiono et al. 1979; Kobayashi 1980). They showed that the $H/V$ peak is due to the horizontal-vertical polarization of the Rayleigh waves. Lachet and Bard (1994), Kudo (1995), and Bonnefoy-Claudet et al. (2008) also confirmed the correlation between the $H/V$ peak frequency and the site resonance frequency. They concluded that the $H/V$ ratio can be used to identify the fundamental frequency of soft soils and observed that the vertical component of Rayleigh wave motion almost vanishes in the vicinity of fundamental $S$-wave resonant frequency. However, the amplitude of this peak is not well-correlated with the $S$-wave amplification at the site’s resonant frequency. Instead, it is highly sensitive to some parameters such as Poisson’s ratio near the surface. Hence, no straightforward relation exists between the $H/V$ peak amplitude and the site amplification.

Nakamura (1989), on the other hand, proposed that the $H/V$ ratio is a reliable estimation of the site response of $S$ waves. According to him, $H/V$ provides reliable estimates not only about resonant frequencies but also the corresponding $S$-wave amplification as the division of spectral horizontal component by the “reference” vertical component remove both the source and Rayleigh wave effects. A comparison between observed amplifications where derived from earthquake records and those observed by $H/V$ at more than 30 sites demonstrates that $H/V$ from microtremor is almost always smaller than that of earthquake records (ESG98 1998). This suggests that the Nakamura technique could provide a lower-bound estimate to the actual amplification. The nature of noise wavefield and its application for site-effects studies were summarized in a literature review by Bonnefoy-Claudet et al. (2006).

Haghshenas et al. (2008) have compared the site amplification of the microtremor $H/V$ method for estimating site effects with the results from two other techniques, the standard site-to-reference spectral ratio (SSR) and the horizontal and vertical spectra at a single station (HVSRE). The fundamental frequencies of all three methods coincide with each other. A significant part of where they disagree corresponds to thick, low-frequency, continental sites where the natural noise level is often very low and $H/V$ noise ratios do not exhibit any clear peak. The second important finding of Haghshenas et al. (2008) is the absence of correlation between $H/V$ peak amplitude and the actual site amplification measured on site-to-reference spectral ratios. There are, however, two statistically significant results concerning the amplitude of the $H/V$ curve: the peak amplitude may be considered as a lower-bound estimate of the actual amplification indicated by SSR (it is smaller for 79% of the 104 investigated sites), and, from another point of view, the difference in amplitude exhibits an intriguing correlation with the geometrical characteristics of the sediment/basement interface: large SSR/$H/V$ differences might thus help to detect the existence of significant 2D or 3D effects. Incidentally, we note that $H/V$ spectral ratio of ambient noise is a qualitative tool (not a precise tool) for the site amplification.

H/V SPECTRAL PROCESSING AND ANALYSIS

To process and analyze the ambient noise observations, we used the J-SESAME 1.08 software developed specifically for use in the $H/V$ technique (SESAME, European research project WP12-Deliverable D23.12, 2004). J-SESAME is provided as a tool for the easy implementation of the recommendations outlined in this document. J-SESAME offers several options for data processing, provides the recommended processing options as defaults, and is a useful tool for the easy implementation of the recommendations outlined in this document. The
The general design of J-SESAME is based on a modular architecture. There are basically four main modules: 1) browsing module; 2) window selection module; 3) processing module; and 4) display module. Figure 4 shows the graphical user interface of J-SESAME and selected windows.

The main processing module is developed in FORTRAN 90 for computing $H/V$ spectral ratio. It performs $H/V$ spectral ratio computations and other associated processing such as DC-offset removal, filtering, smoothing, and merging of horizontal components, etc., on the selected windows for individual files or alternatively on several files as a batch process. The main functionalities of the processing module are:

- Fast Fourier transform (FFT), including tapering,
- Smoothing with several options,
- Merging two horizontal components with several options,
- $H/V$ spectral ratio for each individual window,
- Average of $H/V$ ratios, and
- Standard deviation estimates of spectral ratios.

For each site observation the stationary portion of the whole signal was selected using at least 10 windows of 40–70 s length. Each windowed signal was processed applying these steps: 1) baseline correction; 2) 5% cosine tapered; 3) FFT for the three components; 4) smoothing the FFT spectra using the Konno and Ohmachi (1998) algorithm, which accounts for the different number of points with bandwidth smoothing of 30. The spectrum of the two horizontal components were merged with a quadratic mean and divided by the spectrum of the vertical component. A visual selection of the frequency peaks with amplitude greater than 2 was applied based on the criteria for reliability of results discussed in the SESAME (2004) guidelines for the implementation of the $H/V$ ambient noise technique. Figure 5 shows the criteria for reliability of $H/V$ results.

Each observation point provides an $H/V$ spectral ratio, which enables an estimation of the fundamental frequency ($f_0$) and the corresponding amplitude level ($A_0$) at the observed site. All the measurement points at soft Nile deposits show a

<table>
<thead>
<tr>
<th>HOLOCENE</th>
<th>PILOLIOENE - PLEISTOCENE</th>
<th>MIOCENE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern times</td>
<td>&lt;500</td>
<td>Old Nile branches were silted up and two branches (Dannietta, Rosetta) survived and remained active.</td>
</tr>
<tr>
<td>Historic times</td>
<td>5000-500</td>
<td>Smooth shoreline and arcuate typical of wave dominated.</td>
</tr>
<tr>
<td>Pre-historic time</td>
<td>10,000</td>
<td>Stable sea level and the Delta were subjected to human control.</td>
</tr>
<tr>
<td>Bilgas</td>
<td>(50 m)</td>
<td>Silts and sandy mud like present-day river deposits. Constitute the agricultural soil of Delta. With African derivation.</td>
</tr>
<tr>
<td>Mit Ghamr</td>
<td>(700m)</td>
<td>Fluvial gravely sands with minor clays interbedded with dunes sands. Main aquifer in the Nile Delta. Derived from Ethiopian highlands and Red Sea hills Bulan Formation is its marine equivalent in offshore wells. Formed of clay and shale with minor sands (deltic, coastal, marine).</td>
</tr>
<tr>
<td>EL-Wastani</td>
<td>(300m)</td>
<td>Quartz sand and shales with gravel few carbonates in the NW of Delta.</td>
</tr>
<tr>
<td>Kafir El sheikh</td>
<td>(1200m)</td>
<td>Interbedded red-brown silty clays with this fine-grained sand derived from highly vegetated areas with extremely wet climate.</td>
</tr>
<tr>
<td>Abu Madi</td>
<td>(250m)</td>
<td>Interbedded sands and shales gas producing horizon.</td>
</tr>
<tr>
<td>Rosetta</td>
<td>(50m)</td>
<td>Anhydrite, correlated with the Messinian evaporates of the Mediterranean basin.</td>
</tr>
<tr>
<td>Sawasim</td>
<td>(965m)</td>
<td>Coarse-grained sands and gravels derived from the cretaceous and Eocene rocks.</td>
</tr>
<tr>
<td>Sadi Salem</td>
<td>(1000m)</td>
<td>Clays with few interbeds of dolomitic marls and minor sandstones.</td>
</tr>
</tbody>
</table>

▲ Figure 3. Composite columnar section of the subsurface deposits of the Nile Delta as proposed by Rizzini et al. (1978).
Figure 4. The graphical user interface of J-SESAME. Selected windows are shown in gray.

Criteria for a reliable H/V curve
i) $f_0 > 10 / l_w$
   and
ii) $n_c (f_0) > 200$
   and
iii) $\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f_0 > 0.5Hz$
   or $\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f_0 < 0.5Hz$

Criteria for a clear H/V peak (at least 5 out of 6 criteria fulfilled)
   i) $\exists f \in [f_0/4, f_0/2] \ | \ A_{HV}(f) < A_0/2$
   ii) $\exists f' \in [f_0, 4f_0] \ | \ A_{HV}(f') < A_0/2$
   iii) $A_0 > 2$
   iv) $f_{peak}[A_{HV}(f) \pm \sigma_A(f)] = f_0 \pm 5$
   v) $\sigma_A(f_0) < \varepsilon (f_0)$
   vi) $\sigma_A(f_0) < \theta (f_0)$

Threshold Values for $\sigma_A$ and $\sigma_A(f_0)$

<table>
<thead>
<tr>
<th>Frequency range [Hz]</th>
<th>&lt; 0.2</th>
<th>0.2 – 0.5</th>
<th>0.5 – 1.0</th>
<th>1.0 – 2.0</th>
<th>&gt; 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon (f_0)$ [Hz]</td>
<td>0.25 $f_0$</td>
<td>0.20 $f_0$</td>
<td>0.15 $f_0$</td>
<td>0.10 $f_0$</td>
<td>0.05 $f_0$</td>
</tr>
<tr>
<td>$\theta (f_0)$ for $\sigma_A(f_0)$</td>
<td>3.0</td>
<td>2.5</td>
<td>2.0</td>
<td>1.78</td>
<td>1.58</td>
</tr>
<tr>
<td>$\log \theta (f_0)$ for $\sigma_{logHV}(f_0)$</td>
<td>0.48</td>
<td>0.40</td>
<td>0.30</td>
<td>0.25</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Figure 5. Diagram showing the criteria for reliability of results.
significant amplification level ($2 < A_0 < 6$) at the fundamental frequencies in the range of 0.9 to 1.2 Hz. However, the fundamental frequency becomes larger (up to 5 Hz) at the gravels and gravelly sand of the deltaic phase with sand dunes. Figure 6 shows the distribution of the higher fundamental frequency and $H/V$ spectral ratio with respect to the geological map of the Nile delta.

The fundamental frequency band of 0.9 to 1.2 Hz was correlated with the geologic section of the Nile delta basin in Figure 2. It is consistent with the soft sediments of the Holocene (Neonile episode) where thickness ranged from 5 to 15 m. The shear-wave velocity ($V_s$) is estimated for the soft sediments corresponding to the fundamental frequency band using the formula $V_s \approx f_0 \cdot 4h$, where $h$ is the thickness of the layer. The estimated $V_s$ ranges from 24 to 54 m/s.

**DISCUSSION AND CONCLUSIONS**

Estimation of local site effects for a highly populated urban area located on a sedimentary basin is a crucial component of seismic hazard assessment. This study employs the analysis of $H/V$ spectral ratio from ambient noise to map the fundamental frequencies and amplitude of the soft sediments in the Nile delta basin.

We carried out microtremor observations at 120 sites along three parallel profiles crossing the Nile delta from south to north. We processed and analyzed the observations using the J-SESAME software following the SESAME guidelines. The peak amplitude ratio was picked at frequency ranges from 0.89 to 1.21 Hz. The study showed that the frequency range of the peak $H/V$ ratio falls mainly in a narrow band ranging from 0.9 to 1.2 Hz for the entire Nile delta basin. The average $H/V$ amplitudes in this frequency range vary from 2.1 to 5.8.

Numerically, the coincidence between the shear-wave resonance frequency and the frequency of the peak of the $H/V$ ratio is confirmed for the uppermost layer where the impedance contrast is high (Malischewsky and Scherbaum 2004). We compared the results of the $H/V$ spectral ratio with the geological structure beneath the Nile delta and observed a good correlation between the fundamental frequencies and the distribution of the Neonile sediments.

The shear wave velocity for the soft sediments corresponding to the fundamental frequencies was calculated to have a very low velocity ranging from 24 to 54 m/s. This low velocity value may be attributed to the high water content (Flores-Estrella et al. 2007) and the nature and characteristics of the soft Neonile sediments (Nile alluvium) in this region, which constitutes the agriculture soil of the delta, silty sand, and soft clay as shown in Figure 2. It overlies the clastic sediments of fluvial continental sediments named the Mit Ghamer formation (Figure 3) that represents the aquifer in the Nile delta.

Finally, we compared the results of this study with others that concerned a sedimentary basin in an urban environment (e.g., Williams et al. 1993; Satoh et al. 2001; Dutta et al. 2007). The effect of the low-velocity surficial layer in our study is consistent with studies done in San Francisco and Mexico City.
by Robert et al. (1993) and Flores-Estrella et al. (2007), where there is also a very-low-velocity surface layer ($V_s \sim 50$ m/s at frequency 1 Hz) with a similar thickness (10 to 14 m) around San Francisco Bay and Mexico City.

This study shows an intermediate resonance frequency at the Nile delta basin, where the $H/V$ peak at frequency $\sim$1 Hz, which is related to the surficial geology. There is a possibility of both short- and long-period ground vibration (resonance) in the entire Nile delta basin. This could cause severe damage to the soft- and long-period structures in the basin, especially high-rise buildings and bridges at the two branches of the Nile River. Hence, this study strongly recommends that special effort be made to design and construct seismically resistant structures. In addition to highlighting the importance of the $H/V$ spectral ratio of the ambient noise in determining site characteristics and seismic zonation for urban regions, our study provides important information about sediment formation of the main aquifer in the Nile delta basin. We recommend that future work be undertaken to test the validity of using the ambient noise $H/V$ spectral ratio as an exploration tool for the gas-producing horizon in the Nile delta, using longer records during all four seasons of the year.

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