Some new theoretical considerations about the ellipticity of Rayleigh waves in the light of site-effect studies in Israel and Mexico

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Resumen

La amplificación del movimiento del terreno, como resultado de la presencia de suelos blandos, es un fenómeno común en áreas urbanas y bien identificado como un factor que incrementa el daño y el número de pérdidas humanas. Por otro lado, para el análisis de la amenaza sísmica, el estudio de la elipticidad de las ondas de Rayleigh se ha hecho más popular en el contexto del uso de registros de vibraciones ambientales, además, los resultados pueden ser usados en la inversión de la estructura de velocidades. Los efectos de sitio normalmente pueden ser modelados a partir de un perfil de velocidades simple, dado el alto contraste de impedancias en la estructura somera del subsuelo. Por lo tanto, el análisis y el entendimiento de las implicaciones de un modelo tan simple como una capa sobre un semiespacio (LOH, por sus siglas en inglés) son de suma importancia, no sólo teórica sino también práctica. Adicionalmente, para registros de vibraciones ambientales todavía no se cuenta con un modelo teórico que explique de manera satisfactoria los resultados de los cocientes espectrales *H*/*V*; un punto de inicio sobre la elipticidad de las ondas Rayleigh es la fórmula exacta propuesta por Malischewsky y Scherbaum (2004). Es possible mostrar que un modelo tan simple como LOH puede producir una gran variedad de curvas *H*/*V*-versus-frecuencia y mostramos como ejemplo las curvas *H*/*V* con más de un máximo para los casos de Israel y de México. Este fenómeno se atribuye a la contribución de capas adicionales, esto es, que el primer máximo se asocia con la frecuencia de resonancia de la primera capa y los máximos secundarios se asocian con las frecuencias de resonancia de capas más profundas. Demostramos que con un modelo LOH obtenemos dos máximos, para ciertos valores del módulo de Poisson. Sin embargo, este modelo simple no puede explicar las curvas experimentales consideradas, para las que posiblemente se requieran perfiles de velocidades más complejos y modos de propagación superiores. Estas consideraciones pueden implicar restricciones para los valores del módulo de Poisson, que normalmente no se toman en consideración. En conclusión, estas investigaciones analíticas y semi-analíticas son indispensables para un mejor entendimiento del comportamiento de la elipticidad de las ondas de Rayleigh en su uso para estudios de efectos de sitio.

Palabras clave: Elipticidad de ondas Rayleigh (*H*/*V*), estudios de efectos de sitio en Israel y en México.

Abstract

It is well-known that ground motion amplification due to soft soils, common in urban areas, is a major contributor to increasing damage and number of causalities. Indirectly, the study of Rayleigh-wave ellipticities has recently gained considerable popularity in the context of studying ambient seismic vibrations for seismic hazard analysis. The output can be integrated into the inversion process for the velocity structure. Due to the strong impedance contrast in the shallow subsurface structure, local site effects are often fairly well predicted by simple models. Therefore, a thorough theoretical understanding of even a single layer over half-space (LOH) is not only of theoretical but also of considerable practical interest. Adding to this argument is the fact that an accepted theoretical model for the interpretation of *H*/*V*-measurements from ambient vibrations, still has to be developed. A useful starting point for the theoretical investigation of the ellipticity of Rayleigh waves is the exact formula derived by Malischewsky and Scherbaum (2004). It can be shown, that already the simple LOH model is able to produce a great variety of *H*/*V*-versus-frequency curves with different character. We cite observations from Israel and Mexico as an example of *H/V*-curves with more than one maximum. This phenomenon is usually contributed to additional layers, where the first maximum is connected with the shear-resonance frequency of the first layer and the secondary maximum with a resonance frequency of a deeper layer. We demonstrate that already the simple LOH model yields two peaks in a certain range of Poisson ratios. However this simple model cannot explain the experimental curves under consideration, where more complex models and higher modes are necessary. These considerations can yield constraints for Poisson ratios which are otherwise less controlled. In conclusion, such theoretical investigations of analytical or half-analytical character are necessary for a better understanding of the behaviour of the ellipticity of Rayleigh waves and its use for site effect studies.

Key words: Ellipticity of Rayleigh waves (*H/V*), site effect studies in Israel and Mexico

El mayor placer en el mundo para el ser humano es descubrir nuevas verdades; el siguiente es librarse de viejos prejuicios.
Friedrich II, Rey Prusiano (1712-1786)

The most vigorous pleasure for a human being in the world is to discover new truths; the next to this is to get rid of old prejudices.
Friedrich II, Prussian King (1712-1786)

Introduction

It is well-known that the ellipticity of Rayleigh waves is important in applying the popular *H/V* method for the estimation of local site effects and the characterization of shallow site structure. *H/V* spectral ratios of ambient vibrations are increasingly used in investigations of local site amplifications during strong earthquakes, as ambient noise is often dominated by Rayleigh waves (Scherbaum *et al*., 2003; Bard, 1998). It can be even said that the *H/V* spectral ratio technique, originally introduced by Nogoshi and Igarashi (1971), also known as Nakamura's method (Nakamura, 1989; 2009), has become the primary tool of choice in many of the ambient noise related studies (see e. g., Muciarelli *et al*., 2009).

However, the fundamentals of the *H/V* technique are controversial [the history and different opinions are discussed e. g., by Bonnefoy-Claudet *et al*. (2006) and Petrosino (2006)]. These different opinions even refer to the term *H/V* technique itself. The spectral ratio *H/V* is usually taken from ambient noise but sometimes also from earthquakes [see e. g., Zschau and Parolai (2004) or Flores Estrella (2009)] or artificial explosions. Following Chávez-García (2009), microtremors can be explored in two directions: estimation of a local transfer function and estimation of the subsoil structure and from there obtain site effects by modelling. He points out that the use of *H/V* spectral ratio of microtremors to estimate a local transfer function has a weaker physical basis than spectral ratios relative to the reference site. Nevertheless, it has been successful to estimate site effects. This success has been explained by the assumption that microtremors consist of body waves [see e. g., Nakamura (1989)] contrary to the observation in the papers by Bard (1998) and Scherbaum *et al*. (2003) cited above. On the other hand, it is interesting to note that an explanation based on the opposite assumption that microtremors mainly consist of surface waves is also successful [see e. g., Fäh *et al*. (2001)]. This is especially true for great shear-wave contrasts between layer and half-space which was theoretically confirmed by Malischewsky and Scherbaum (2004). By interpreting Rayleigh waves as P and S waves with complex angles of incidence their interrelation in interpreting *H/V* spectra becomes obvious. It is not the aim of this paper to investigate these complicated ramifications of seismic wave theory, which we let to be done in a future paper. Rather, we focus on a special feature, namely on the existence of more than one peak in the *H/V* curve and demonstrate theoretically under which conditions it can be attributed to the ellipticity of Rayleigh waves alone. These considerations were carried out in the framework of an German-Israelian project "Interdisciplinary study of the internal structure and current crustal deformation in the Dead Sea Transform (DST) with applications to seismic hazard in the region." The DST (see Fig. 1) is the most impressive seismically active feature in the Middle East. Return periods for large destructive earthquakes are of hundreds of years or more, but also medium-large events (e. g., the 1927 Jericho earthquake with M ~ 6.2) may cause substantial damage and loss of life (see seismicity map in Fig. 2).

Concerning *H/V* measurements in Israel, Zaslavsky *et al*. (2008) come to the conclusion: "Our results point to the fact that *H/V* spectral ratio from ambient noise adds very useful information and when integrated with other different data sources allows us to obtain a systematic picture of site effects in the investigated region. The application of this methodology is very important in Israel and probably other regions where big earthquakes present a long return period, but might exhibit a high seismic risk."

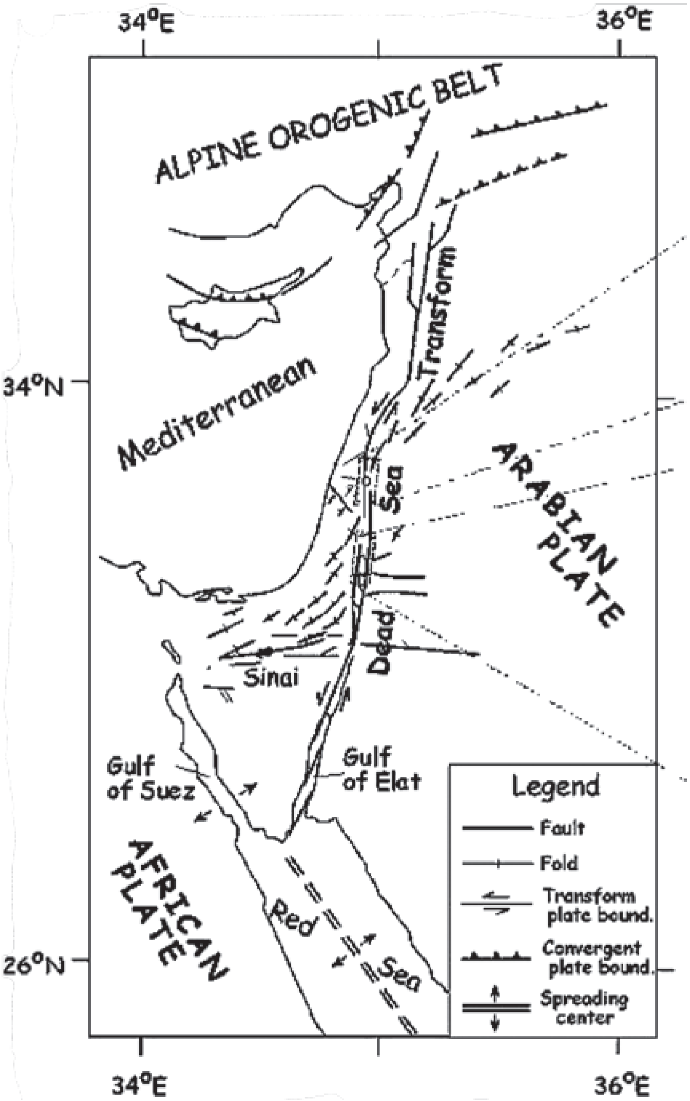

Fig. 1. Regional plate setting at the Dead Sea Transform (DST).

A lot of *H*/*V* measurements were carried out in the Lod-Ramla urban area of Israel (see Fig. 3). They exhibit in several cases curves with more than one peak and these additional peaks are usually attributed to resonances in deeper layers. These measurements do not directly refer to the DST. However, theoretical implications derived from them have methodological character and are applicable not only for the DST zone but everywhere in the world in zones with high seismic risk including the valley of Mexico City.

After theoretical considerations in next chapter we will present and discuss measurements from the urban Lod-Ramla area mentioned above, from the northern part of the DST, the Mehola test site (see Fig. 3) and from the valley of Mexico, D. F. (see Fig.12). The parameters of the considered models, so far available, are summarized in Table 1. They come partly from borehole measurements and were now and then changed and simplified for our theoretical requirements.

Two peaks of the Rayleigh-wave ellipticity (*H*/*V*) in a model "Layer over Half-Space (LOH)"

An useful starting point for the following considerations is the exact formula for the ellipticity $\chi = H/V$ of the Rayleigh fundamental mode according to Malischewsky and Scherbaum (2004) which yields χ as a function of the layer and half-space parameters, and the non-dimensional frequency $\bar{f}$:

$$\chi = \chi\,(r_s, r_d, v_1, v_2, \bar{f}) \qquad (1)$$

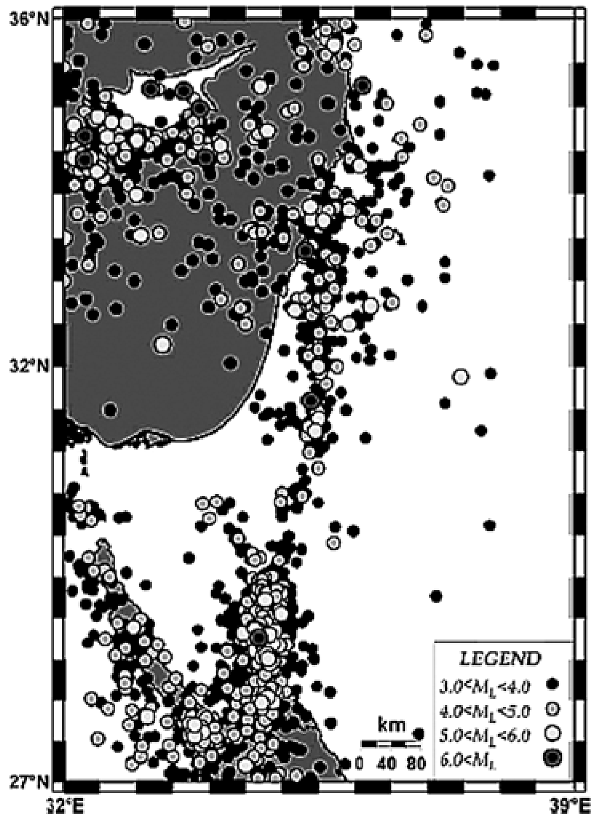

Fig. 2. Seismicity map of the Israel region in the period 1900-2000 after the Geophysical Institute of Israel.

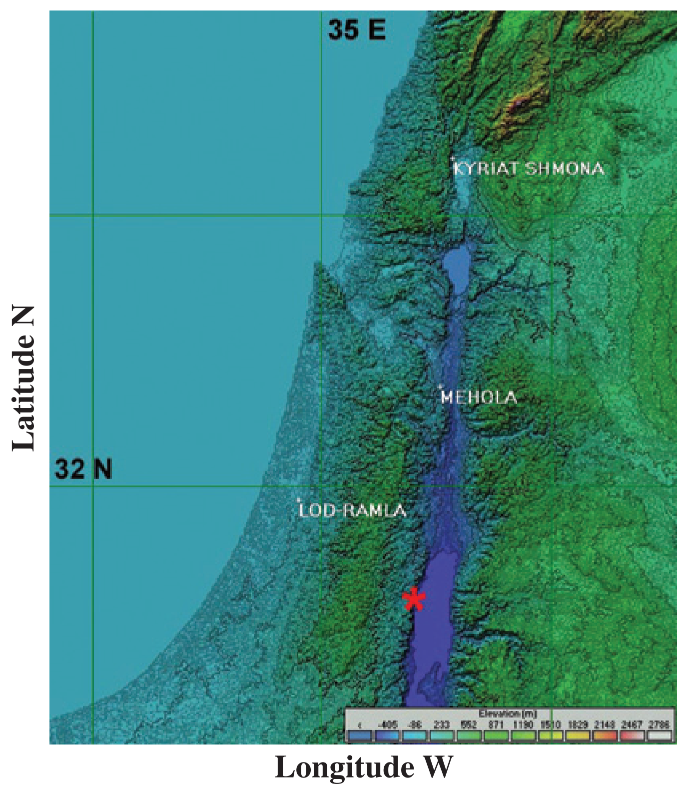

Fig. 3. Geographical location of the test sites Kyriat Shmona, Mehola, and Lod-Ramla in Israel mentioned in the article and location of the epicentre of the 11 July, 1927 earthquake.

Table 1

model	**layer**	**β [m/s]**	**ρ [g/cm³]**	**d [m]**	**ν**
KS	1	365	1.7	15	
	2	1476	2.3	∞	0.3449
LOD25	1	415		25	
	2	500		7	
	3	600		55	
	4	800		40	
	5	1250		40	
	6	1900		∞	
Example2	1	250	1.7	40	
	2	650	1.8	50	
	3	900	1.9	110	
	4	1900	2.2	∞	
Texcoco	1	34	1.1	20	0.491
	2	79	1.5	22	0.491
	3	475	2.6	∞	0.463

Parameters of the models under consideration: β = shear-wave velocity, ρ = density, d = thickness of layers, ν = Poisson ratio.

In particular $r_s = \beta_1/\beta_2$ is the ratio of shear-wave velocities between layer (β_1) and half-space (β_2), $r_d=\rho_1/\rho_2$ is the density contrast and ν_1 and ν_2 are the Poisson ratios of the layer and Half-space, respectively. The non-dimensional frequency is defined by $\bar{f} = d/\lambda_{\beta_1}$, with the layer thickness d and the shear-wave length in the layer λ_{β_1}. The complicated formula (1) can be found at Malischewsky and Scherbaum (2004) or Malischewsky *et al*. (2006). Usually it is assumed for the model "1 layer over half-space (LOH)" that χ as a function of frequency has one peak or one maximum depending on the material parameters whereas a model with 2 layers over a half-space may have two peaks [see e. g., Wathelet *et al*. (2004)]. However, a more careful theoretical analysis exhibits also two peaks for a 1-layer model within a certain parameter range. Fig. 4 presents two 3D-pictures of χ for a simplified 1-layer model of the Israelian test site Kyriat Shmona (see Fig. 3) in dependence on ν_1 and $\bar{f}$ with different ViewPoints. Fig. 4a better demonstrates the transition from one maximum of χ to two peaks, and Fig. 4b clearer shows the special ν_1 range with two peaks.

Additionally, we present, in Fig. 5, a 2D picture with the dependence of $\bar{f}$ for the primary and secondary peak or the maximum, against ν_1.

By varying the shear contrast r_s of the model we are able to demonstrate the (ν_1, r_s) domain for two peaks in the LOH-model (see Fig. 6). The ν_1 range is maximum for r_s = 0; i. e., for a layer with fixed bottom (LFB), and ceases to exist for r_s>0.36.

Tran, (2009) has found a necessary and sufficient condition for the existence of two peaks for the LFB-model (compare with Fig. 6), which is

$$0.2026 < \nu < 0.25. \tag{2}$$

The number 0.2026 is a solution of the equation

$$1 - 2\sqrt{\gamma}\sin\left(\sqrt{\gamma}\frac{\pi}{2}\right) = 0 \tag{3}$$

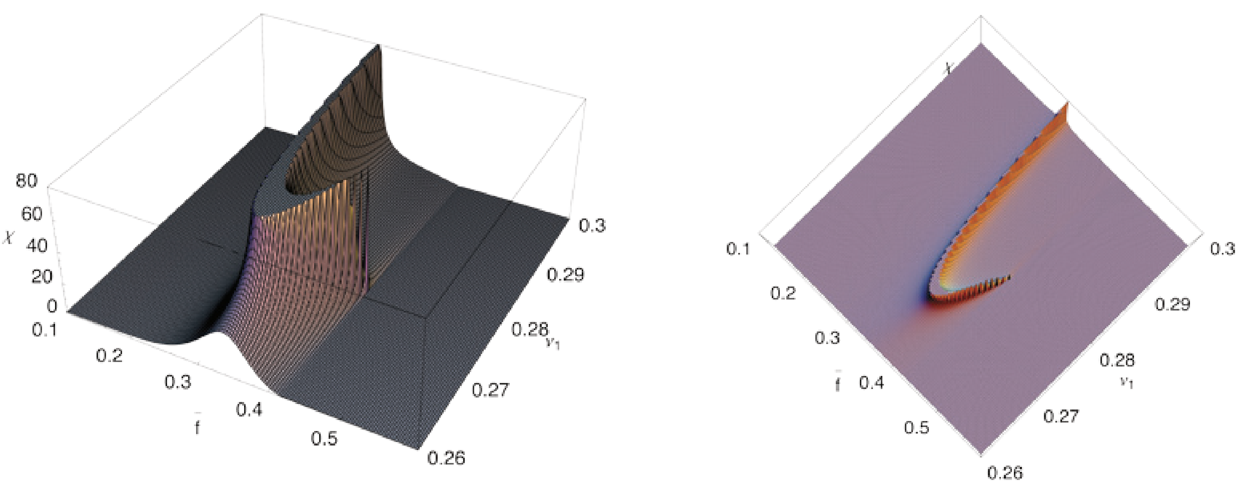

Fig. 4. 3D picture of the *H/V* ratio χ in dependence on $\bar{f}$ and ν_1,
Left: a) ViewPoint → ($\bar{f}$, ν_1, χ) = (1.3 - 2.4, 2). Model KS,
Right: b) ViewPoint → ($\bar{f}$, ν_1, χ) = (0.4, -0.4, 5.5). Model KS.

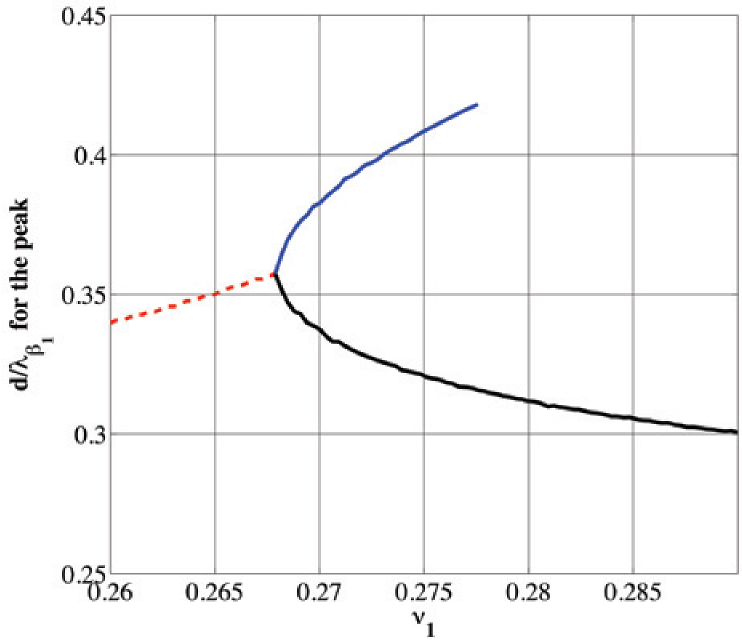

Fig. 5. Dependence of $\bar{f} = d/\lambda_{\beta 1}$ for the primary peak (black, full), the secondary peak (blue, full), and the maximum (red, dashed) against v_1. Model KS.

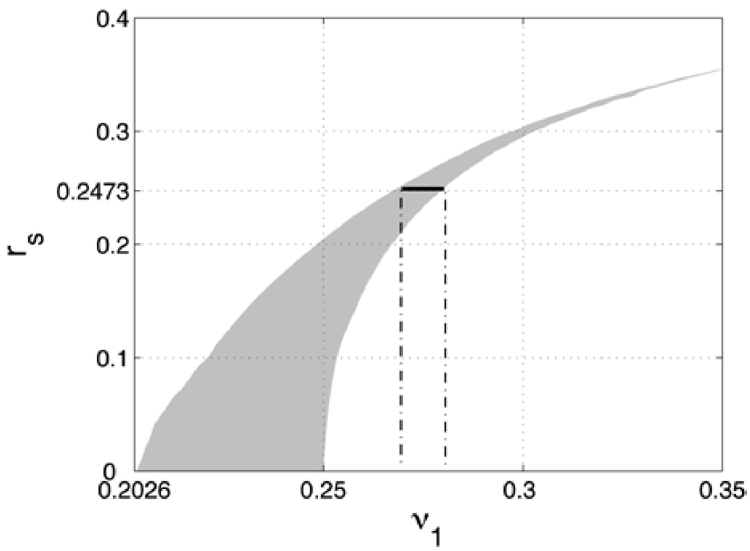

Fig. 6. The domain with two peaks of χ (grey) in the (v_1, r_s) plane. The value of r_s for the KS model is indicated.

with

$$\gamma = \frac{1\text{-}2v}{2(1\text{-}v)} .$$

For this model, the frequency of the first peak is always $\bar{f}_1 = 0.25$ (resonance frequency!) and of the second peak

$$\bar{f}_2 = 0.25 + 3.861(v - 0.2026). \qquad (4)$$

The situation is more complicated for the model LOH. Following Tran (2009), the necessary and sufficient conditions for the existence of two peaks in this case are:

$$\text{for } 0.2026 < v_1 < 0.25 : 0 < r_s < F(v_1, v_2, r_d)$$
$$\text{for } 0.25 < v_1 < v_0(v_2, r_d) : K(v_1, v_2, r_d) < r_s < F(v_1, v_2, r_d)$$
$$\text{with } v_0(v_2, r_d) = 0.3019 + 0.0511 r_d - 0.0183 v_2 - 0.0444 r_d v_2. \qquad (5)$$

These conditions were obtained numerically and the functions F and K are given by

$$F(v_1, v_2, r_d) = A(v_2, r_d) \arctan [B(v_2, r_d) (v_1\text{-}0.2026)],$$
$$K(v_1, v_2, r_d) = C(v_2, r_d) \arctan [D(v_2, r_d) (v_1\text{-}0.25)], \quad (6)$$

with

$$A(v_2, r_d) = 0.297 + 0.061 r_d - 0.058 r_d^2 + 0.17 v_2 - 0.589 r_d v_2 + 0.373 r_d^2 v_2 - 0.284 v_2^2 + 0.817 r_d v_2^2 - 0.551 r_d^2 v_2^2,$$
$$B(v_2, r_d) = 29.708 - 42.447 r_d + 23.852 r_d^2 - 14.309 v_2 + 75.204 r_d v_2 - 59.881 r_d^2 v_2 + 121.37 v_2^2 - 246.328 r_d v_2^2 + 170.027 r_d^2 v_2^2,$$
$$C(v_2, r_d) = 0.3058 - 0.0471 r_d + 0.0092 r_d^2 - 0.0839 v_2 + 0.2918 r_d v_2 - 0.2673 r_d^2 v_2 + 0.1538 v_2^2 - 0.6098 r_d v_2^2 + 0.5056 r_d^2 v_2^2,$$
$$D(v_2, r_d) = 65.9858 - 91.2188 r_d + 47.698 r_d^2 + 137.1766 v_2 - 342.7329 r_d v_2 + 249.2955 r_d^2 v_2 + 67.7489 v_2^2 + 223.5938 r_d v_2^2 - 253.4675 r_d^2 v_2^2. \quad (7)$$

While function F is comparatively precise (its error is less than 1-2 %), the error of K can be up to 5 % in some cases. The critical Poisson ratio varies according to (5) within the bounds:

$$0.2929 < v_0 < 0.353 . \quad (8)$$

This estimation was obtained by assuming $0.3 < r_d < 0.9$ and $0 < v_2 < 0.5$ and it indicates that the influence of v_2 and r_d is not negligible.

Some Measurements and numerical simulations

The area of Lod-Ramla (see Fig. 3) was shaken by the last destructive earthquake on July 11, 1927 nearby Jericho with Richter magnitude about 6.3 or a seismic intensity of VIII on the MSK scale and caused the destruction of a great part of these towns. It can be assumed that such a high intensity from a relatively distant earthquake was probably the result of local site effects, which is very similar to the disastrous earthquake in Mexico City on 19 September; 1985. Site response studies by using ambient vibrations in that area were carried out by Zaslavsky *et al*. (2005). Quite a few of these *H/V* spectral ratios exhibit more than one peak or maximum. Fig. 7 shows two examples.

We realize in Fig. 7a a splitted maximum at 0.9 Hz and 1.2 Hz, respectively, and another maximum is not very well visible between 3 and 4 Hz. The typical shape with two close peaks between 0.9 and 1.4 Hz can be seen in the noise *H/V*, in the transfer function and in the *H/V* spectral ratio of a Red Sea earthquake as well. The second peak at 1.4 Hz is most likely caused by an intermediate hard layer in the subsurface, at the very least is this one possibility of explanation. Fig. 7b shows clearly two maxima at 1.2 and 3.5 Hz. The modelization with SH waves with the SHAKE program [see Schnabel *et al*. (1972)] is moderate for Example2 and excellent for Lod25. If we use a simplified 1-layer model with high shear-wave contrast and varying Poisson ratios in the layer, we observe a behaviour as in Fig. 8 in agreement with our theory. The main peak is stable at 0.9 Hz because of the big shear-wave contrast, but for certain Poisson ratios in the layer a secondary peak appears at 1.5 Hz.

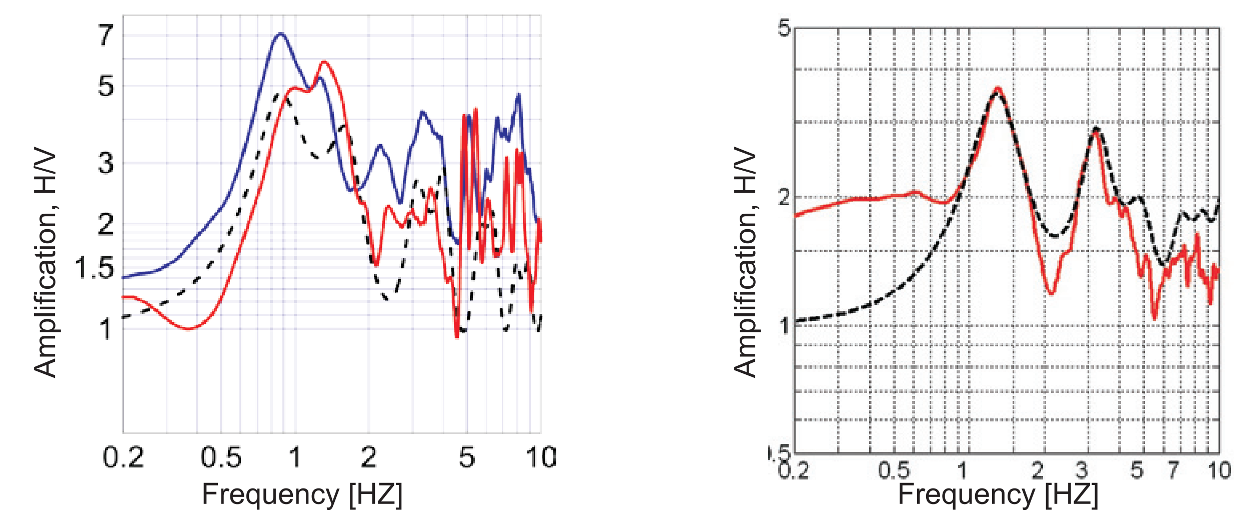

Fig. 7. a) Left: mean *H/V*-noise measurement at the Ramla location (Example2) 36° 25’ 29’’ N 35° 24’ 31’’ E (full, red), analytical modelization with SHAKE (black, dashed), EQ (blue, full); b) Right: mean *H/V*-noise measurement at the Lod location (Lod25, borehole) 36° 29’ 03’’ N 35° 26’ 32’’ E (full, red), analytical modelization with SHAKE (black, dashed).

Now we try a modelization on the basis of multilayer models and Rayleigh-*H/V* by varying the Poisson ratios in the layers and present some snapshots for Example2 in Fig. 9 and for Lod25 in Fig. 10.

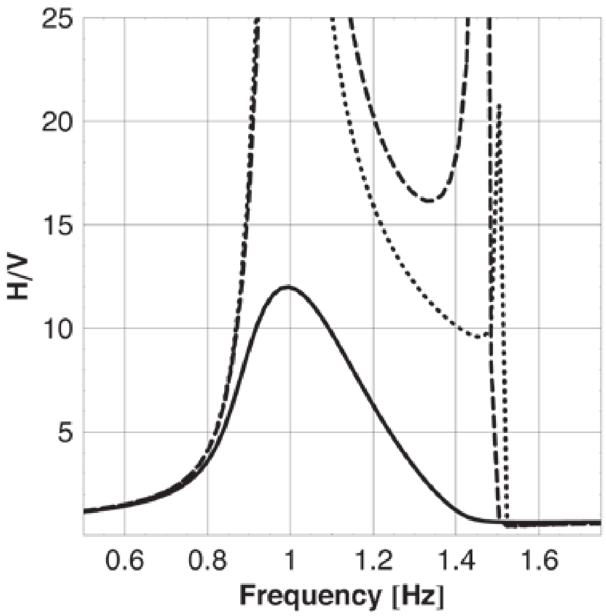

Fig. 8. *H/V* in dependence on frequency for a simplified 1-layer model with varying Poisson ratios in the layer: $\nu_1 = 0.20$ (full), $\nu_1 = 0.258$ (dashed), $\nu_1 = 0.26225$ (dotted) and the parameters $\beta_1 = 300$ m/s, $\beta_2 = 1900$ m/s, $\rho_1 = 1.8$ g/cm^3, $\rho_2 = 2.2$ g/cm^3, $d_1 = 85$ m, $\nu_2 = 0.25$.

We see from Fig. 9a that the first maximum can be explained by Rayleigh's fundamental mode as well and the second maximum by the first higher mode. Further we realize that a certain splitting of the first maximum is observed for the snapshot parameters in Fig. 8b, but on an other amplitude level. However, the difficulties with the amplitude of *H/V* are well known.

Similar tendencies can be observed in the three snapshots for the location Lod25 in Fig. 10. The snapshot top left shows a very good coincidence between the experimental values and the Rayleigh modelization for the first maximum and the fundamental mode and for the position of the second maximum concerning the frequency with the 1st higher mode.

The so-called Mehola experiment with artificial explosions, was carried out in 2004. The investigated area (see Fig. 3) is situated in the structural saddle between the Kinneret-Bet Shean graben and Damia graben corresponding to the intersection of the DST and SE

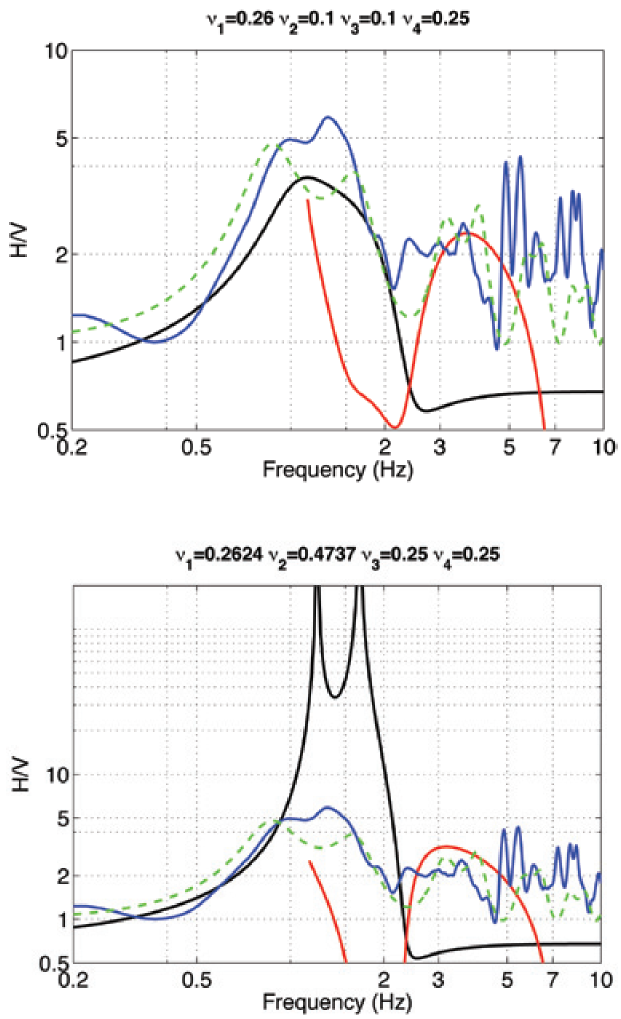

Fig. 9. Two snapshots with different Poisson ratios of theoretical Rayleigh *H/V* for Example2: black: fundamental mode, red: 1. higher mode, blue: experimental noise *H/V*, dashed green: SHAKE-modelization.

extension of the Yagur fault system. It is characterized by loose sediments [exposed alluvium (gravels and soil) and Lisan Formation] in the upper layer of 0 to 50 m thickness overlying hard carbonates of Late Cretaceous-Eocene age. We have analyzed the data collected at stations 1, 2, and 3 in this region by using the software package SESARRAY of the European commission Site Effects assessment using Ambient Excitations (SESAME) SESAME (2005). The explosions and the noise in the time series were processed separately and example curves are presented separately for station 3 in Fig. 11.

The comparatively good agreement between the explosion and noise curves is noteworthy. Further we realize that between 2.5 and 4.3 Hz two maxima appear in outlines.

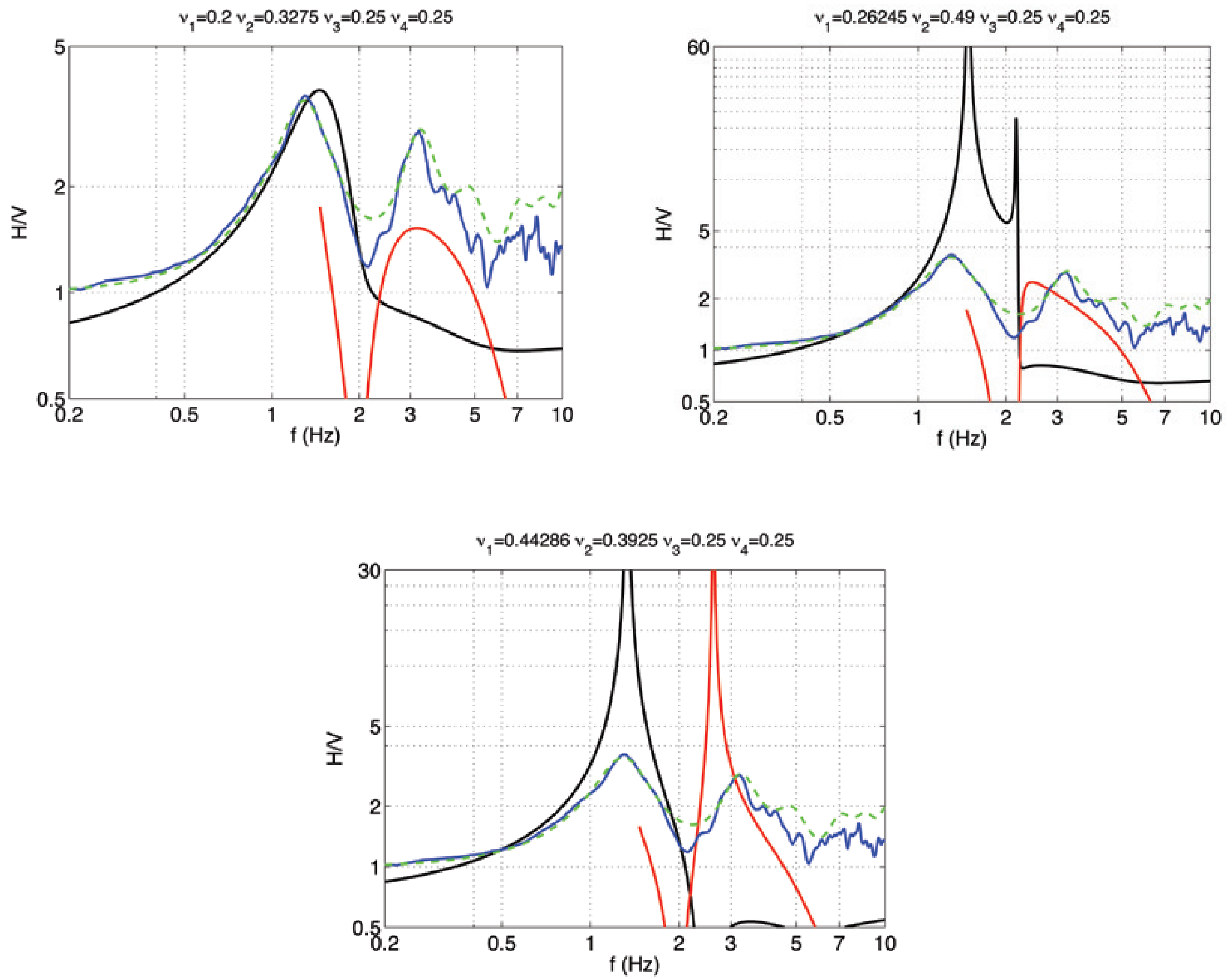

Fig. 10. Three snapshots with different Poisson ratios of theoretical Rayleigh *H*/*V* for Lod25: black: fundamental mode, red: 1st higher mode, blue: experimental noise *H*/*V*, dashed green: SHAKE-modelization.

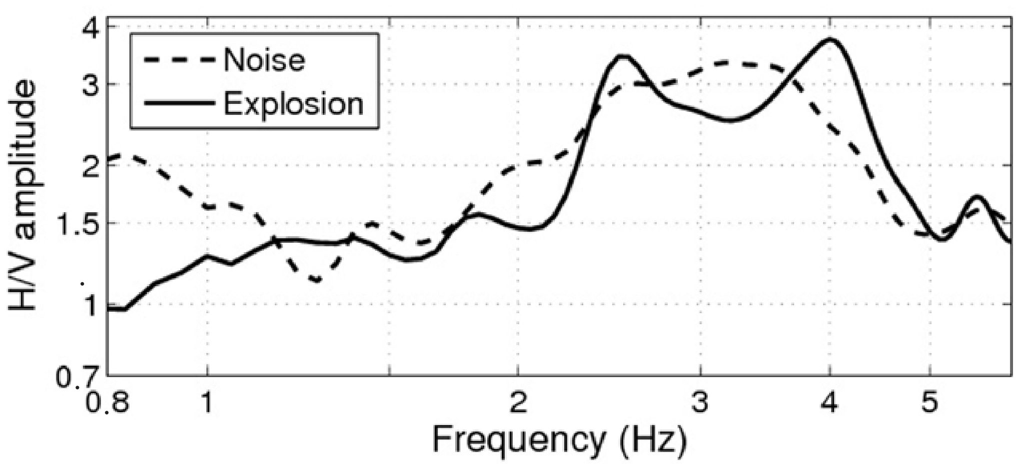

Fig. 11. *H*/*V* spectral ratios for the Mehola experiment at station 3.

A lot of *H/V* measurements were carried out in the valley of Mexico City. As is known, this region has a very high seismic hazard and on the other hand it is an unique region worldwide with an extremely high Poisson ratio (nearby 0.5) in the uppermost layer. We present here only one recent example from the interpretation of measurements in the Texcoco array (see Fig. 12) by Flores-Estrella (2009). Eight events from the time interval 1998-2004 with magnitudes 5.9-7.6 and epicentral distances 266-561 km were analyzed. The time window extended 80 s from the arrival of S waves including some surface waves as well. Fig. 13 shows the experimental *H/V* results together with the theoretical transfer function and our surface-wave *H/V* modelization with the assumed model parameters from Table 1.

We see a very good agreement for the main maximum between the experimental curve, the transfer function, and the Rayleigh-wave ellipticity of the fundamental mode. The stable agreement between the transfer function and the Rayleigh-wave ellipticity is well known for high impedance contrasts between sediment and bedrock. Concerning the other maxima it is clear that *H/V* of the fundamental Rayleigh mode does not contain them because of the extremely high Poisson ratio of the uppermost layers in the Texcoco region. If we would diminish Poisson's ratio artificially, we can obtain two maxima in agreement with our theory (see Fig. 14).

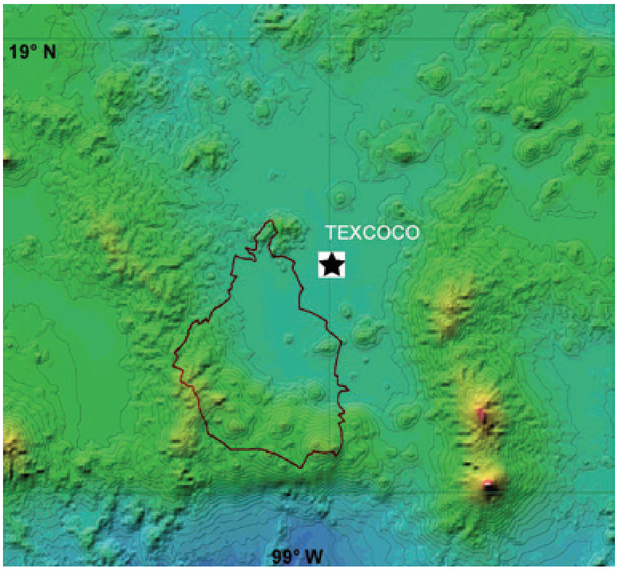

Fig. 12. Geographical location of the Distrito Federal of Mexico City and of the Texcoco array (star).

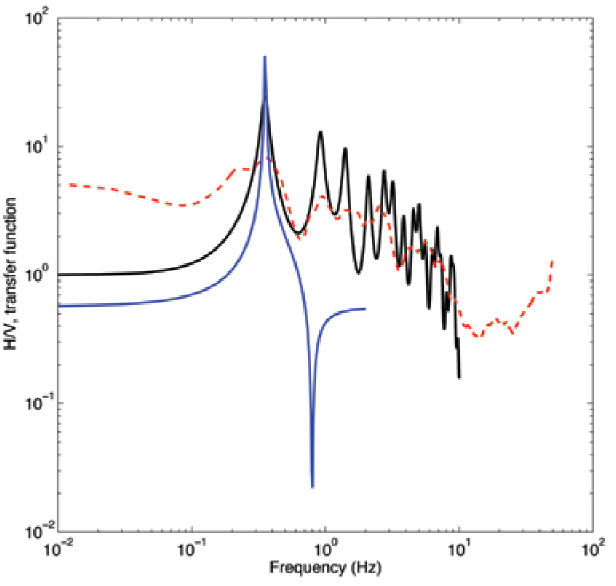

Fig. 13. Experimental spectral ratios *H/V* (red, dashed), transfer function (black, full), ellipticity of the fundamental Rayleigh mode for the Texcoco model (blue, full).

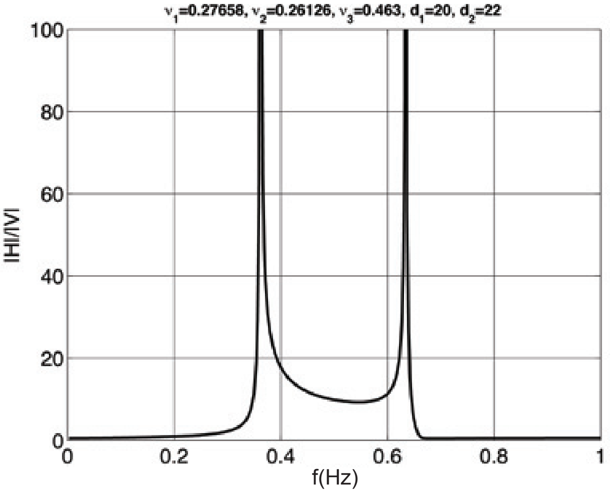

Fig. 14. Rayleigh *H/V* in dependence on frequency for the Texcoco model with changed Poisson ratios in the two layers.

The position of the first peak is more or less stable, but the second maximum does not fall into a region where we would wait for another maximum. We have not analyzed the contribution of higher Rayleigh modes for the other maxima of the Texcoco model, which may be important.

Discussion and conclusions

The application of the *H/V* method is without doubt important for such regions with medium or high seismic risk as Israel and surrounding regions, and Mexico. We have realized that there is a very definite parameter interval in which the theoretical spectral ratio *H/V* of the fundamental Rayleigh mode has two peaks for the model LOH. On the other hand, many observations, from which we specify only a few, exhibit several peaks. Obviously, the simple LOH model is not complex enough to explain the latter ones for the examples under discussion. Here, more complex models and higher modes as in Fig. 9 are necessary. Our intention is to sensitize the seismological community for the phenomenon of more than one peak or maximum of the ellipticity of Rayleigh waves as a function of frequency, which was only marginally considered so far. Naturally, such a consideration has to start with very simple structural models and then swich over to more complex ones. The very simple model of an impedance surface can produce under certain circumstances a weak maximum of *H/V* only [see Malischewsky *et al*. (2008)]. The simplest model being able to generate two peaks for certain model parameters is LOH, which was analyzed here. The existence and position of these secondary peaks is very sensitive to changes of Poisson's ratio. So this conception of two or more peaks for Rayleigh *H/V* in comparison with measurements can yield constraints especially for Poisson ratios, which are otherwise less controlled. The same is true when considering the changing range of prograde Rayleigh motion, which was already carried out for the Mexico basin and the Israelian test site Kyriat Shmona as well [see Malischewsky *et al*. (2006, 2008)].

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