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RESEARCH NOTE

Comment on 'evidence of the dominance of higher-mode surface waves in the lake-bed zone of the valley of Mexico by Shapiro *et al.* (2001)'

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SUMMARY

The purpose of this note is to contribute to the understanding of seismic ground motion in Mexico City. To this end, we (1) compute theoretical transfer functions for various models for the deep structure and the shallow clay layers, (2) study the seismic responses of various sites within the city using spectral ratios (of horizontal motion relative to the motion of nearby rock sites and relative to the vertical motion at the same site) and (3) discuss some characteristics of surface waves for models of the deep structure and the shallow clay layers in the Valley of Mexico.

Key words: crustal model, Mexico City, shallow layers, site effects, surface waves, transfer function.

1 INTRODUCTION

In a recent paper Shapiro *et al.* (2001, hereafter referred to as SSAA) concluded that the wavefield in the lake-bed zone in Mexico City is dominated by higher-mode surface waves with a frequency of 0.4 Hz. They argue that these surface waves are the result of the interaction between the deep structure (mainly a 2 km thickness relatively low-velocity zone) and the shallow sediments of the valley. It is certainly important to understand and quantify the effect of the deep structure in the Basin of Mexico. In fact, Chávez-García *et al.* (1995) analysed the dispersion of surface waves in Mexico City and suggested the interaction of deep and shallow structures, but these authors did not address the dominance of higher modes. In order to accept the dominance of higher-mode surface waves we believe that stronger evidence than the results provided by SSAA is still needed.

2 COMMENTS ON SSAA

SSAA's work is relevant since it tries to explain the phenomena related to the long duration of strong ground motion observed at the lake-bed zone. In a recent paper Shapiro *et al.* (2002) suggested that in order to explain duration of ground motion in Mexico City for subduction earthquakes both the regional structure and the heterogeneity of the source zone (accretionary prism and water layer) must be taken into account.

It has long been recognized that shallow layers (<100 m) of highly compressible, large-water content clays in Mexico City are the most important factors in the seismic response and therefore the cause of the observed damage (i.e. Ordaz *et al.* 1988; Seed *et al.* 1988; Singh *et al.* 1988a,b; Sánchez-Sesma *et al.* 1993; Chávez-García & Bard 1994; Reinoso *et al.* 1997; Reinoso & Ordaz 1999). These site effects vary enormously in form and amplitude within a few kilometres mainly according to the thickness of these layers. SSAA studied the effect of the interaction of the deep and the shallow structures at different locations of the lake-bed zone of the valley, but they only showed results for the ROMA (RM) array (fig. 3 of their work). They concluded that the 0.4 Hz dominant frequency at RM site is due to this interaction but, as far as we understand, this can be explained by a simple 1-D response of the site. Therefore, the question here is: how can we find out the interaction proposed by SSAA in sites that have exhibited different seismic behaviour from site RM in spite of the differences in the clay thickness? Should we expect the same 0.4 Hz dominant frequency at these sites?

3 STRATIGRAPHIES AND OBSERVATIONS

To try to find out the answer to this question we have used SSAA's stratigraphy for site RM to evaluate the seismic response of two other sites, SC and 84 (see Fig. 1), where the shallow stratigraphy is also known (for SC we used the values given by Seed *et al.* 1988 and for site 84 we used those of Reinoso *et al.* 1997). Table 1 shows the deep structure proposed by SSAA and used for the three sites. Tables 2–4 show data for shallow stratigraphies at RM, SC and 84, respectively. Fig. 2(a) shows the 1-D transfer functions for these sites. It is clear from the plots that the 0.4 Hz peak is only present at RM. Peaks at 0.5 and 0.6 Hz are present for SC and 84, respectively, which correspond to the fundamental frequencies of each site due to the presence of the clay deposits. There is a 0.3 Hz peak present at all sites, and it may represent the effect of the 2 km thickness low-velocity structure mentioned by SSAA.

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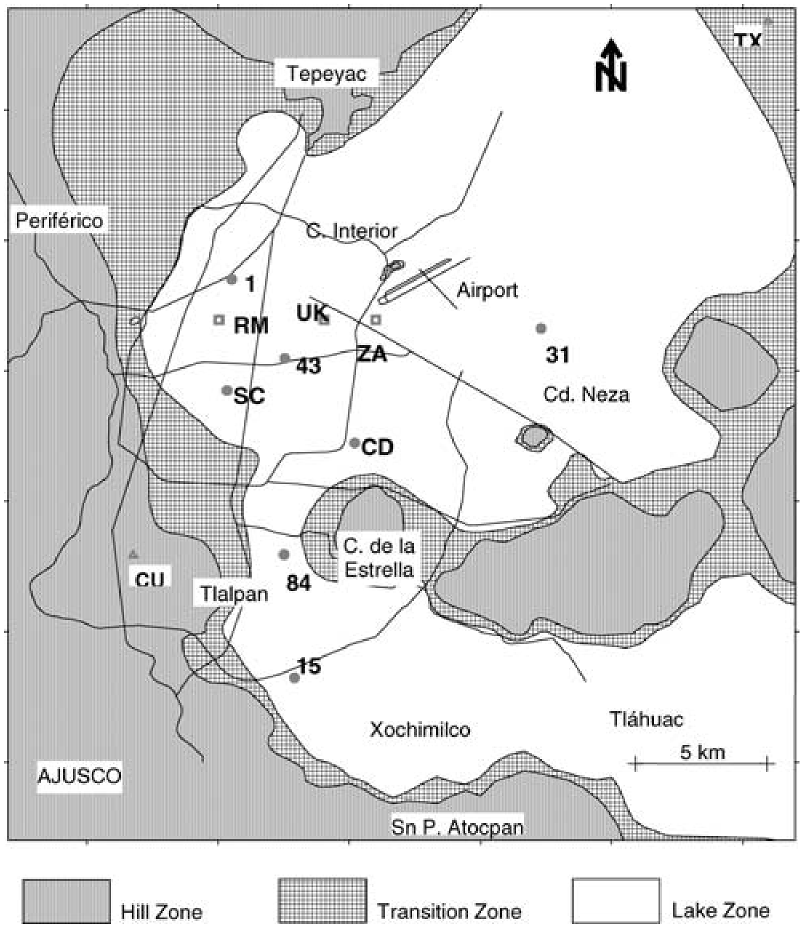

Figure 1. Mexico City: accelerometric stations, geotechnical zones and some important streets and locations.

Table 1. Model 1 used by Shapiro *et al.* (2001) but without the two shallow layers of RM site.

Thickness H (km)	V_p (km s^{-1})	V_s (km s^{-1})	ρ (g cm^{-3})
0.3	2.0	0.4	2.05
0.2	2.5	0.8	2.05
2.0	3.0	1.7	2.2
5.0	5.28	3.05	2.4
12.0	5.71	3.3	2.4
28.0	6.4	3.7	2.7
∞	8.13	4.7	3.3

Table 2. Geological model for site RM (taken from Shapiro *et al.* 2001).

Thickness H (km)	V_p (km s^{-1})	V_s (km s^{-1})	ρ (g cm^{-3})
0.03	0.8	0.05	2.0
0.02	1.2	0.10	2.0

Table 3. Geological model for site SC (taken from Seed *et al.* 1988; Reinoso & Ordaz 1999).

Thickness H (km)	V_p (km s^{-1})	V_s (km s^{-1})	ρ (g cm^{-3})
0.004	0.121	0.070	2.0
0.027	0.130	0.075	2.0
0.007	0.190	0.110	2.0

Table 4. Geological model for site 84 (taken from Reinoso *et al.* 1997).

Thickness H (km)	V_p (km s^{-1})	V_s (km s^{-1})	ρ (g cm^{-3})
0.03	0.138	0.08	1.4

We have substituted the deep structural model used in Fig. 2(a) (Table 1) with the stratigraphy published by Singh *et al.* (1995) that also reaches a depth of 2.5 km (Table 5). The respective 1-D transfer functions using Singh *et al.* stratigraphy are shown in Fig. 2(b). It can be observed that the peak near 0.4 Hz is only present at RM, while for sites SC and 84 the prominent peaks remain at 0.5 and 0.6 Hz, respectively. The peak at 0.3 Hz disappears completely with this more rigid model. This shows that the deep structure, as far as we can observe in our results, does not have a strong influence in the dominant peak of each site. In our opinion, the results depicted in Fig. 2 show that shallow layers dominate the seismic response at the lake-bed zone, and that the enhanced response at 0.4 Hz is due mainly to the very surficial clay deposits at RM.

To emphasize the variability of the fundamental frequency at different accelerometric sites within the valley, we used data from

Table 5. Model 2 (taken from Singh *et al.* 1995).

Thickness H (km)	V_p (km s^{-1})	V_s (km s^{-1})	ρ (g cm^{-3})
0.15	1.38	0.8	2.05
0.21	1.9	1.1	2.05
1.21	2.6	1.5	2.2
0.80	3.46	2.0	2.3
5.00	5.28	3.05	2.4
12.00	5.71	3.3	2.4
28.00	6.4	3.7	2.7
∞	8.13	4.7	3.30

the 1995 September 14 subduction earthquake ($M_w = 7.3$; $H =$ 22 km; 17.0°N and 99.0°W) originated south of Mexico City. As a result of this the north–south records represents the radial component while the east–west signals correspond to the transverse one. We selected nine sites in the lake-bed zone (01, 15, 31, 43, CD, RM, SC, ZA and UK in Fig. 1), which we considered representative of the seismic response of the valley since they cover a wide range of dominant periods and zones. Spectral ratios were obtained for these nine locations with respect to two reference stations: CU and TX, both stations located at the hill zone of the Mexico City Valley (Fig. 1). The site CU represents the seismic response at the base of the soil deposits at depths of 0–150 m (Seed *et al.* 1988; Singh *et al.* 1988a,b; Reinoso & Ordaz 1999), while the record at TX is equivalent to the input motion at the base of the soil layers at a depth of around 1 km (Montalvo-Arrieta *et al.* 2002, 2003). If there were an effect from the deep structure ($<$1 km, in this case) the spectral ratio with TX should exhibit significant differences when compared with CU. Fig. 3 depicts with a thick line these nine spectral ratios of the north–south motion with respect to CU, and with a thin line those with respect to TX (the east–west spectral ratio is not shown since it is very similar to the north–south one). The spectral ratios shape and dominant frequencies are different for each station but similar between the TX and CU ratios. The amplification is larger for the TX ratio since it is located over older deposits. Differences in form, amplitude and dominant frequency between stations are due to the variability in the thickness and wave velocity at the lake-bed zone (Seed *et al.* 1988; Singh *et al.* 1988a,b; Reinoso & Ordaz 1999) and the peak of 0.4 Hz is only present at RM.

We have also calculated the H/V ratios for the radial and transverse components of all stations in Fig. 3, as has been done by SSAA for RM. Fig. 4 depicts these H/V ratios for the two horizontal components, which are very similar to those shown in Fig. 3. The peak in 0.4 Hz is clearly visible at RM but represents the site effect. The variability of form and amplitude of the site response shows that the effect of the shallow layer is dominant, and the peak in 0.4 Hz corresponds only to RM site.

3.1 Distribution of displacement with depth

SSAA used the distribution of displacements with depth as a possibility to discriminate between the fundamental and the first higher mode. They compare the vertical displacements observed at four stations with borehole accelerographs (RM, TL, UK, ZA), with the theoretical distributions of displacement computed for the RM structural model. Comparing the theoretical vertical displacements at RM with data from other stations with different geotechnical characteristics needs some justification.

To show the sensitivity of the theoretical distributions of displacements we computed the normalized vertical eigenfunctions for six different models in which we combined the two deep layers used previously (Tables 1 and 5) with the surficial layers for the accelerografic stations RM, SC and 84 (Tables 2–4). The normalized vertical eigenfunctions are plotted for periods of 2.0, 2.5 and 3.0 s with dotted, dashed and solid lines, respectively, and for the fundamental mode and the first higher mode of the vertical displacement of Rayleigh waves. The normalized eigenfunctions for each mode and period are depicted in Figs 5 and 6 for the models 1 and 2. SSAA explain that using their model, the normalized vertical displacement for the fundamental mode decreases more rapidly than for the

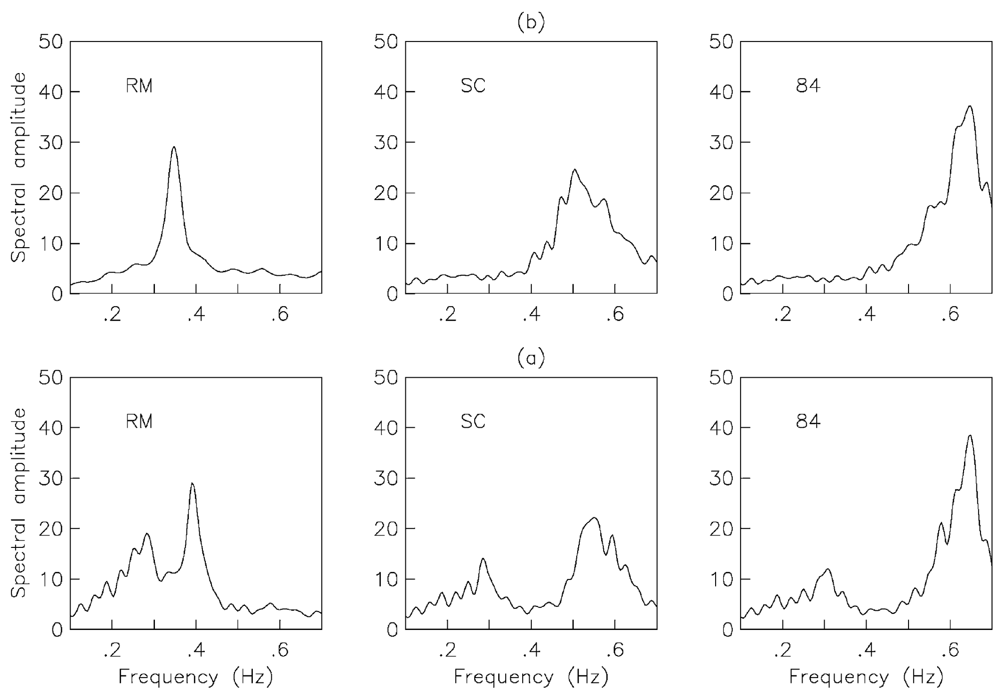

Figure 2. 1-D response for vertical incidence of *SH* waves using RM, SC and 84 models (Tables 2–4, respectively) (a) model 1 (Shapiro's model) and (b) model 2 (Singh *et al.* model).

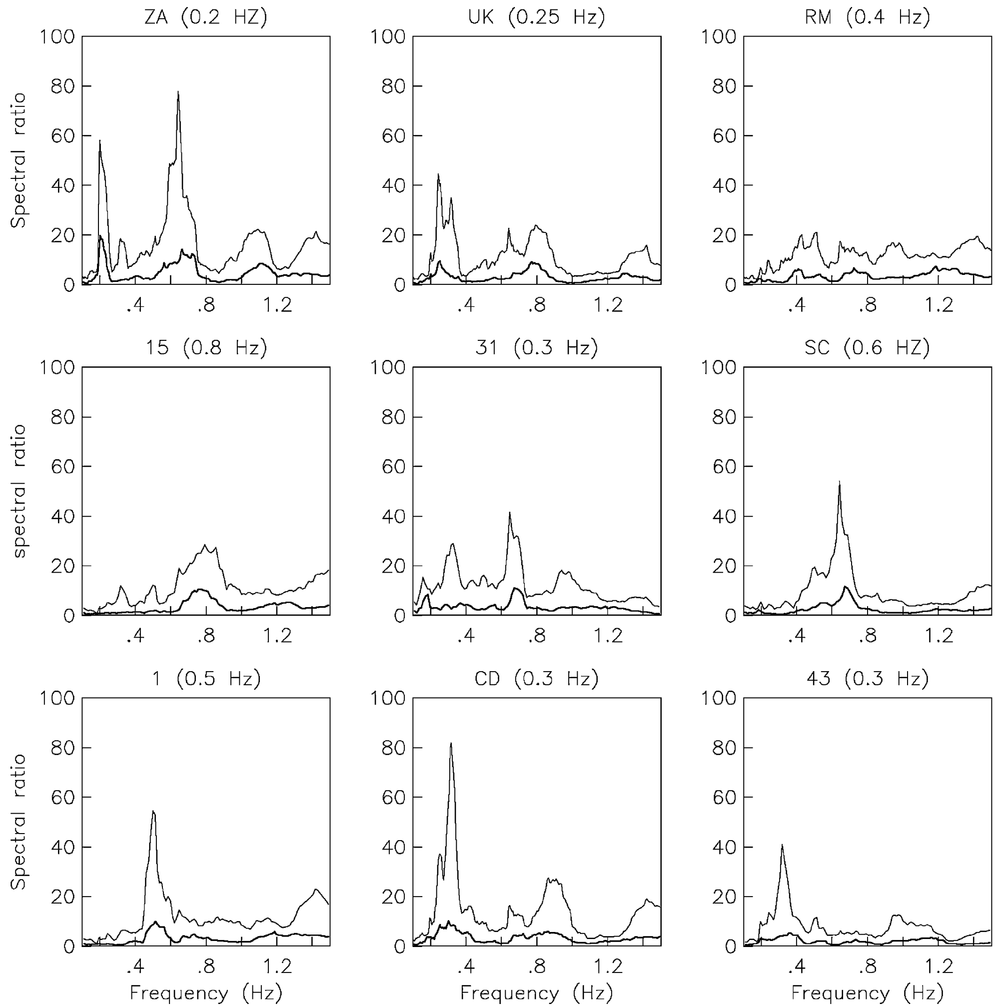

Figure 3. Spectral ratios of 01, CD, 43, 15, 31, SC, ZA, UK and RM sites with respect to CU (thick line) and TX, for the 1995 September 14 earthquake, north–south component. The dominant frequency of each site is also shown.

first higher mode, and this difference allows one to discriminate between the fundamental and the first higher mode. Using model 2 for the deep layers and considering the same two surficial layers of RM as done by SSAA, the normalized vertical displacement for the fundamental mode does not decrease more rapidly than for the first higher mode (see model 2 + RM in Fig. 6) as it does in SSAA's model (model 1 + RM in Fig. 5). The differences between the theoretical displacement amplitude for the fundamental and the first higher mode are small. To discriminate between them it is necessary to have very accurate data.

We have also shown in Figs 5 and 6 the observed vertical displacements with their standard deviation taken from fig. 6 of SSAA for RM, TL, UK and ZA. It can be seen that the normalized vertical displacement is quite different for almost all six cases computed. The decision of whether the fundamental or the first higher mode is present will depend on which combination is used. For example the original model of SSAA (model 1 + RM) shows that the first higher mode is present and not the fundamental mode, whereas model 1 + 84 may indicate the contrary. On the other hand, the vertical displacements of model 2 + SC cannot provide a judgement to discriminate between the fundamental and first higher modes.

Even if SSAA's model were used with different surficial layers (model 1 + SC and model 1 + 84 in Fig. 5), the theoretical normalized vertical displacements do not show a more rapid decrease for the fundamental mode than for the first higher mode. So, it is not clear under which assumptions SSAA compared the observed displacements for TL, UK and ZA with the theoretical normalized vertical displacements computed for model 1 + RM.

Singh *et al.* (1997) have already noted that there is a risk of generalizing the results of RM site to other sites in the valley in which deformations may differ by a factor of 2–3. Moreover, the distribution of the theoretical displacements is very sensitive to the structural model. Therefore, it is necessary to use an accurate structural model for each station to have an objective discrimination by comparing the information of several stations with their theoretical displacements. In SSAA's work it is not mentioned why they constructed a structural model for the intermediate layers (2.5 km) underlying the 50 m thick soft sediments in RM instead of using the model that had been already published by Singh *et al.* (1995), which was used in this work to construct model 2 (Table 5).

In order to obtain such a detailed discrimination between the fundamental and the first higher mode of Rayleigh waves, we believe that it is necessary to have smaller standard deviations of the observed displacements and a well-known structural model for each station.

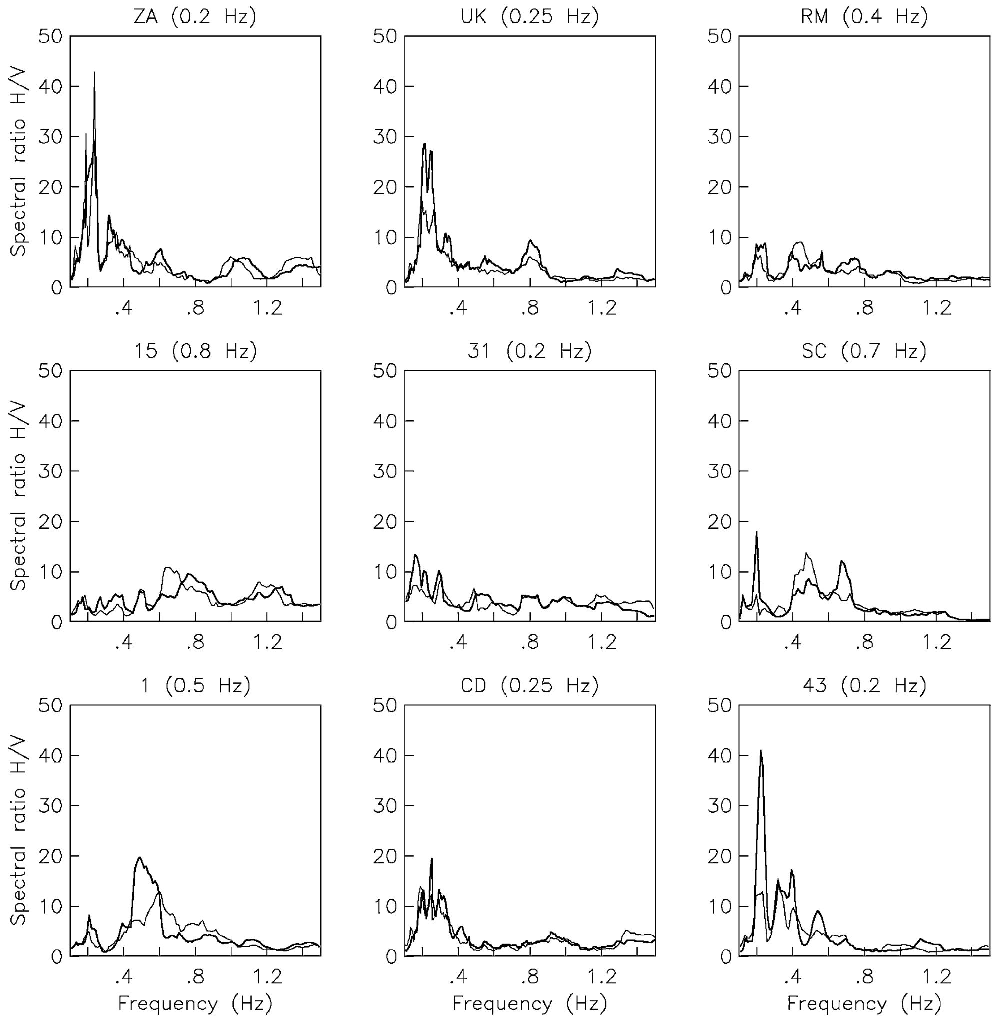

Figure 4. *H*/*V* ratio for the horizontal components of the 1995 September 14 earthquake (thick line corresponds to north–south direction) for the same sites as Fig. 3. The frequency associated to the largest amplitude is depicted for each site.

4 CONCLUSION

In summary, there is a great deal of variability in the site response within the Valley of Mexico (Figs 2–4). However, consistent features seen, for example, in comparisons to responses of stations CU and TX (outside the 'lake zone') show that the superficial clay layer in the valley is the principal factor controlling the site response (such as a dominant frequency of 0.4 Hz at station RM but other frequencies elsewhere). Subsequently, an ambiguity arises as to what wave-type dominates the site response (Figs 5 and 6): a surface wave higher mode that penetrates significantly deeper than the clays but that has a surface response largely controlled by them, or a fundamental mode which propagates almost entirely within the clays, or some combination of these two. The degree of uncertainty in measured data, relative to the computed eigenfunctions for various velocity–depth models and wave models, strongly suggests that it is too early to claim any one of these explanations is uniquely correct.

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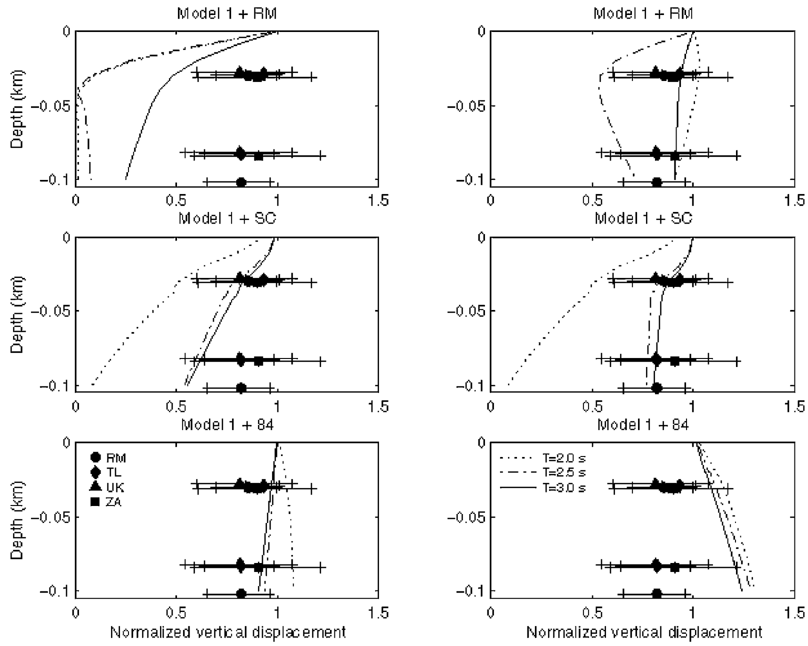
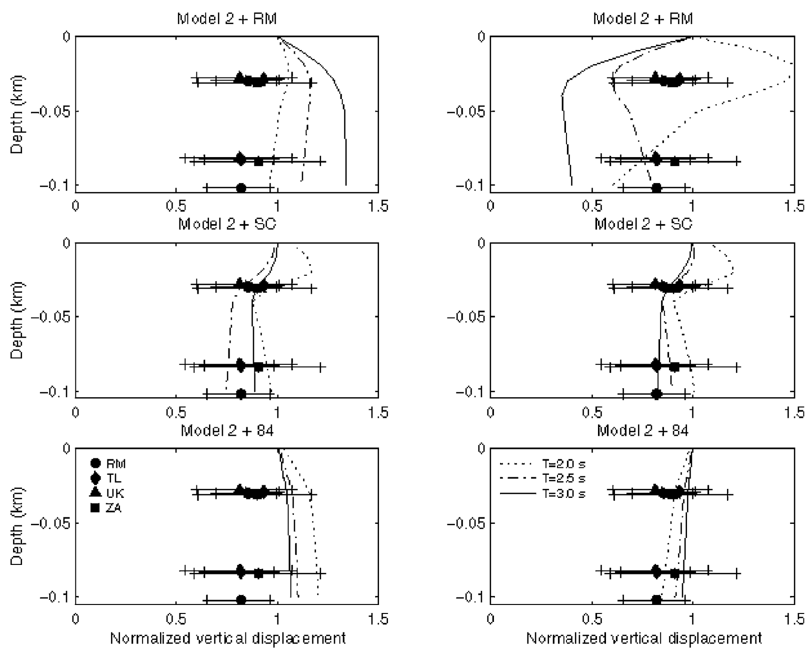


(a) (b)

Figure 5. Eigenfunctions of (a) the fundamental and (b) the first higher modes of vertical component of Rayleigh waves for the following: model 1 + RM (top), model 1 + SC (middle) and model 1 + 84 (bottom). The normalized vertical displacement measured at different depths in four locations: RM, TL, UK and ZA, with horizontal bars indicating the standard deviations taken from fig. 6 of Shapiro *et al.* (2001).



(a) (b)

Figure 6. Eigenfunctions of (a) the fundamental and (b) the first higher modes of vertical component of Rayleigh waves for: model 2 + RM (top), model 2 + SC (middle) and model 2 + 84 (bottom). The normalized vertical displacement measured at different depths in four locations: RM, TL, UK and ZA, with horizontal bars indicating the standard deviations taken from fig. 6 of Shapiro *et al.* (2001).

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