Estimating strong ground motions at great depths

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ESTIMATING STRONG GROUND MOTIONS AT GREAT DEPTHS

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ABSTRACT - In this paper, ratios of peak ground acceleration (PGA), velocity (PGV) and displacement (PGD) and response spectral acceleration (SA) of the ground motion at the surface and at different depths are estimated using shear-wave velocity profiles of rock sites, information on Q in the upper crust and recorded ground motions from rock sites. The results are compared with those reported in the literature for those sites with strong-motion instruments at great depths. As expected estimated ground motions at depth are, in general, lower than those on the surface. Also it is found that the estimated ratios do not show much variation with depth except for high-frequency strong-motion parameters for profiles with high attenuation (Q=10) where ground motions at great depths can be higher than those at the surface. However, it is unlikely that such a low value of Q will occur in practice at depths down to 2km. When details of the near-surface velocity and attenuation structure are not known it is found that the commonly used factor of two (accounting for the effect of the free surface) is a reasonable conservative first estimate at all depths.

1. Introduction

Large-scale engineering projects, such as tunnels, require estimates of the earthquake ground motions at depth to which the construction maybe subjected to during its operating life. Even though it is believed that underground structures are significantly less vulnerable to earthquake shaking than structures on the surface, estimates of the ground shaking to be design against need to be provided to the design engineers. Recently proposed (and constructed) rail tunnels in the Alps include sections at depths greater than 1km where there is little observed data available on which to base estimates of the motions expected. Most boreholes containing strong-motion instruments are less than 100m deep and most of these are at soil sites, whereas at great depths the tunnels pass through bedrock. The advent of KiK-Net in Japan with instruments at up to 2km will provide valuable observational data but since at each KiK-Net site there is only one station at the surface and one at depth it is not possible to study how ground motions vary with depth. For tunnelling projects the depth of the tunnel varies along its path therefore consistently derived ground motions estimates are required for many depths.

At present, in the Alps, a number of long deep base rail tunnels have just been completed, are under construction, or are in the design stage. Examples of these tunnels are: the Gotthard base tunnel and the Lötschberg base tunnel in Switzerland, the Brenner base tunnel in Austria and the Lyon-Turin tunnel connecting France and Italy. Since the level of seismicity in the Alps is reasonable high, these tunnels need to be designed to withstand earthquakes. Underground structures have been found to be less vulnerable to damage from earthquakes than those on the surface (e.g. Hashash et al., 2001). Usually, seismic design loads for underground structures are characterized in terms of deformations and strain imposed by the surrounding ground (e.g. Hashash et al., 2001) but, as with surface structures, inertial forces caused by ground accelerations are also considered in their design. Hence, estimates of the ground motions to be expected at depths are required. At present, however, there is little information available on which to base these estimates.

Ground motions at depths are likely to be considerably different to those at the surface due to these factors (e.g. Fukushima et al., 1995):

- the effect of the free surface, in theory, means that the motion at depth is two times lower than that at the surface;
- rock at the surface is, in general, softer (lower wave-velocities), than those at depth therefore the motion at the surface will have been amplified with respect to the motion at depth;
- the attenuation of high frequencies is less at depth than at the surface (e.g. Abercrombie, 1997);
- interference between the ascending and descending waves and diffraction phenomena can also diminish the motions at depth.

2. Previous studies

In the literature there exist a number of publications on ground motions at depth, however, most of these are based on observations at less than 100m and also from soil sites. Recent tunnels include sections at much greater depths and within rock therefore many of these previous studies are of limited use for this study. At beginning of 2001 a survey of borehole instruments operating at depth was conducted (the results can be accessed at: http://www.crustal.ucsb.edu/~steidl/research/ArrayTable.htm). It lists a number of rock borehole sites with instruments operating at depths of greater than 100m, namely: Whitshell Pinarig, Manitoba (Canada) (maximum depth of 420m within granite) ; Vineyard Canyon, Parkfield, (USA) (maximum depth of 198m) ; Tomioka (Japan) (maximum depth of 950m within sandstone); Shiroyama (Japan) (maximum depth of 239m) ; Oroville (USA) (maximum depth of 475m within fractured rock) ; Joaquim North, Parkfield (USA) (maximum depth of 198m) ; Iwaki (Japan) (maximum depth of 330m within sandstone) ; Cajon Pass (USA) (maximum depth of 2900m within soft rock). Also the KiK-Net network in Japan (http://www.kik.bosai.go.jp/kik/index_en.shtml) includes many instruments at depths greater than 100m.

Four previous studies on the observed ratio between the motion at depth and on the surface are those by De Luca et al. (1998), Fukushima et al. (1995), McGarr & Fletcher (2005) and Shimizu et al. (1996).

De Luca et al. (1998) show Fourier spectral ratios between ground motions at the surface and those at depth (depths between 400m and 1410m) under a mountain (Massif Gran Sasso, Italy). The mountain is composed of relatively soft limestone. They find that these ratios are not strongly affected by depth. The maximum ratio is about four at a frequency of about 5Hz.

Fukushima et al. (1995) study the motions at three sites in Japan: Iwaki (instruments on the surface, at 20, 70, 130, 200 and 330m), Tomioka (instruments on the surface, at 6, 100, 251, 660 and 950m) and Etchujima (instruments on the surface, at 40 and 100m). The Iwaki site is composed of sandstone until a depth of about 300m and then granite at greater depths. Shear-wave velocities are between 840m/s at the surface and 2.8km/s at depth. Tomioka is composed of sandstone, siltstone and tuff with shear-wave velocities between 520 at the surface to 2.8km/s at depth. The site at Etchujima is underlain by sand and clays with shear-wave velocities between 110 and 460m/s.

Fukushima et al. (1995) provide estimates of the average ratio between the maximum acceleration at depth and the maximum acceleration on the surface from 20 earthquakes for Iwaki, 16 earthquakes for Tomioka and 23 earthquakes for Etchujima. These ratios show that the ratio between the PGA at depth and at surface does not change greatly with varying depth, e.g. for Tomioka the ratio varies between 0.33 and 0.23 for depths between 100 and 950m.

McGarr & Fletcher (2005) study the ground motions induced by local (less than 10km) coal mining activity. All stations considered are on hard rock (shear-wave velocities greater than 1.5km/s). They calculate the average ratio between the PGA on the surface (eight stations) and the PGA at about 600m (one station) and find a factor of 2.2, which they attribute to the effect of the free surface.

Shimizu et al. (1996) also study ground motions in a mine (Kamaishi Mine, Japan) at the surface and at depths of 140, 315 and 615m. The mine is in a region of Paleozoic and Mesozoic sedimentary formation and Cretaceous granite. They calculate the ratio between PGA on the surface and at depth for 41 earthquakes and find that the ratio varies with depth: at a depth of 615m they find ratios between two and four and for depths of 140 and 315m a ratio between 140 and 315m.

3. Proposed method

The following estimation method based on models of generic rock profiles of velocity and attenuation characteristics is proposed here. The two generic rock profiles (one for very hard rock, $V_{s,30}$=2.8km/s, and on for soft rock, $V_{s,30}$=618m/s) proposed by Boore & Joyner (1997) were used for shear-wave velocity and density values. Accurate Q estimates for the upper few kilometres of the crust are difficult to obtain because there are few deep borehole recording sites. Abercrombie (1998) provides a review of Q estimates for this depth range. Most Q values seem to fall between 10 and 50 therefore these values were chosen in order to bracket the most likely range of values. Abercrombie's examples show that Q varies with depth but this has been neglected here for simplicity. Also neglected in this method is the effect of the interference between the ascending and descending waves and diffraction phenomena.

Boore (2003) provides a computer program (`site_amp`) for the calculation of amplification due to the presence of a profile of varying shear-wave velocity and intrinsic attenuation. This program was used to compute the amplification curves presented here by computing the expected amplification at the surface and at different depths (the generic profiles were used up until the depth under consideration). The shear-wave velocity at the base of the site profile was assumed to be 3.5km/s and the density was assumed to be 2.8g/cm^3, which are common choices for these variables. The angle of incidence has been chosen as 90°. The effect of the free surface is included by multiplying the ratios obtained by two.

4. Fourier amplitude spectral ratios

Figure 1 shows the Fourier amplitude spectral ratios for the four different profiles (generic rock with Q=10 and Q=50 and generic very hard rock with Q=10 and Q=50) computed using the method outlined above for depths between 0 and 2200m in steps of 200m and frequencies between 0.1 and 20Hz (periods between 0.05 and 10s).

The spectral ratios show that except for high frequencies (>5Hz) ground motions are of lower amplitude that those at the surface due to the effect of the free surface and also site amplification due to the presence of lower shear-wave velocities near the surface than at depth. This is in agreement with the observational results presented above where ground motions at depth are lower than those observed at the surface. Ground motions at softer sites (e.g. the generic rock site) show larger spectral ratios due to higher site amplifications due to lower shear-wave velocities. Depth has a limited effect on the level of the amplification due to lower shear-wave velocities near the surface since the strong velocity gradient that leads to significant amplification is confined to the top few hundred metres.

For high frequencies, however, ground motions at depth can be significantly higher than those at the surface due to lower attenuation at depth. The amplitude of high frequency ground motions can be expected to increase with increasing depth due to lower attenuation, as observed by, for example, Abercrombie (1997).

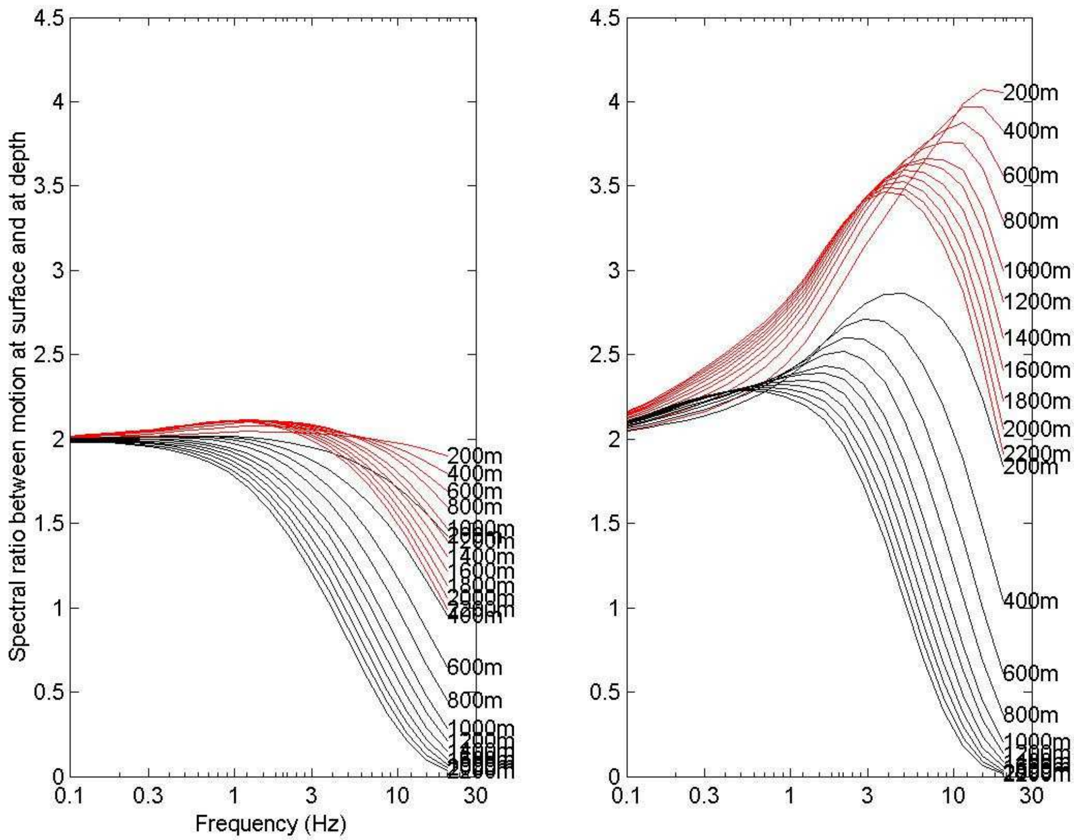

Figure 1. Estimated Fourier amplitude spectral ratios between ground motions at surface and at varying depths estimated for the generic very hard rock site (left-hand side) and generic rock site (right-hand side) for two Q values (black Q=10 and red Q=50).

If Figure 1 is compared to the spectral ratios estimated by De Luca et al. (1998) for depths between 400 and 1410m [the depths of the data of De Luca et al. (1998)] it can be seen that the results for the generic rock profile with Q=10 matches reasonably well although the maximum amplification is slightly lower [about 2.8 in Figure 1 as opposed about 4.2 found by De Luca et al. (1998)]. These differences are to be expected since the profiles of the site of De Luca et al. (1998) with respect to shear-wave velocity and Q are not known and are unlikely to be similar to those of the generic rock site.

5. Ratios of strong-motion parameters

The individually processed strong-motion data released on CD ROM by Ambraseys et al. (2004) were used to assess the expected ratio between strong-motion parameters on the surface and at varying depths using the spectral ratios derived above. All the records from rock sites (330 horizontal components) on the CD ROM were used. Their Fourier amplitude spectra were computed and divided by the spectral ratios estimated for each of the four generic rock profiles to obtain estimated Fourier amplitude spectra at depth. These Fourier amplitude spectra were then inverse Fourier transformed to obtain the predicted ground acceleration at depth. This assumes that the phase spectrum of the motions does not change with depth. For each pair of observed surface acceleration time-history and estimated acceleration time-history at depth the ratio between different strong-motion parameters was computed.

Figures 2-9 show the estimated mean and mean plus and minus one standard deviation ratios between strong-motion parameters on the surface and at depth constructed using the 330 input ground motions.

The figures show that except for high frequency ground-motion parameters (PGA and SA at 0.1s) for profiles with high attenuation (Q=10) the ground motions at depth are smaller than those at the surface by factors up to about four reflecting the findings for spectral ratios estimated above. In addition the ratios of ground-motion parameters are not strong affected by depth. For PGA and SA at 0.1s for profiles with high attenuation ground motions at depth can be significantly higher than those at the surface, up to a factor five for PGA at 2km for the soft rock profile with Q=10. It is unlikely that such a factor will be observed in reality because such low values of Q are expected only close to the surface and not over 2km. In general the effect of the free surface is the most important factor in the assessment of motions at depth and a factor of two seems to be a reasonable conservative estimate of the corrective factor for assessing ground motions at depth in the absence of detailed near-surface velocity and, especially, attenuation information.

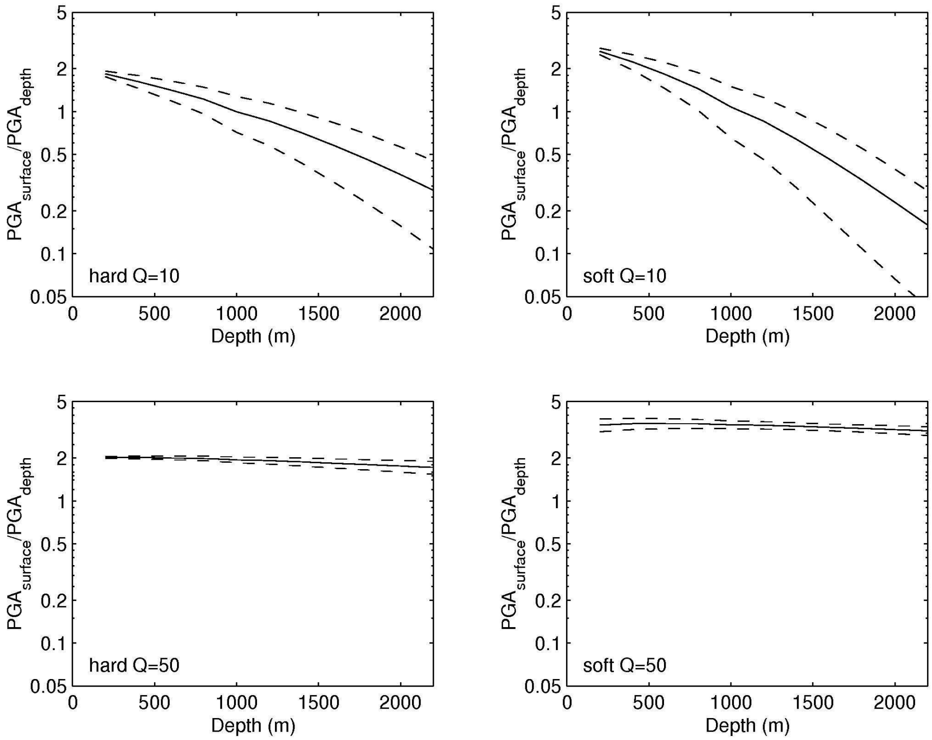

Figure 2. Estimated mean and mean plus and minus one standard deviation ratios between PGA on surface and at varying depths for the four considered profiles.

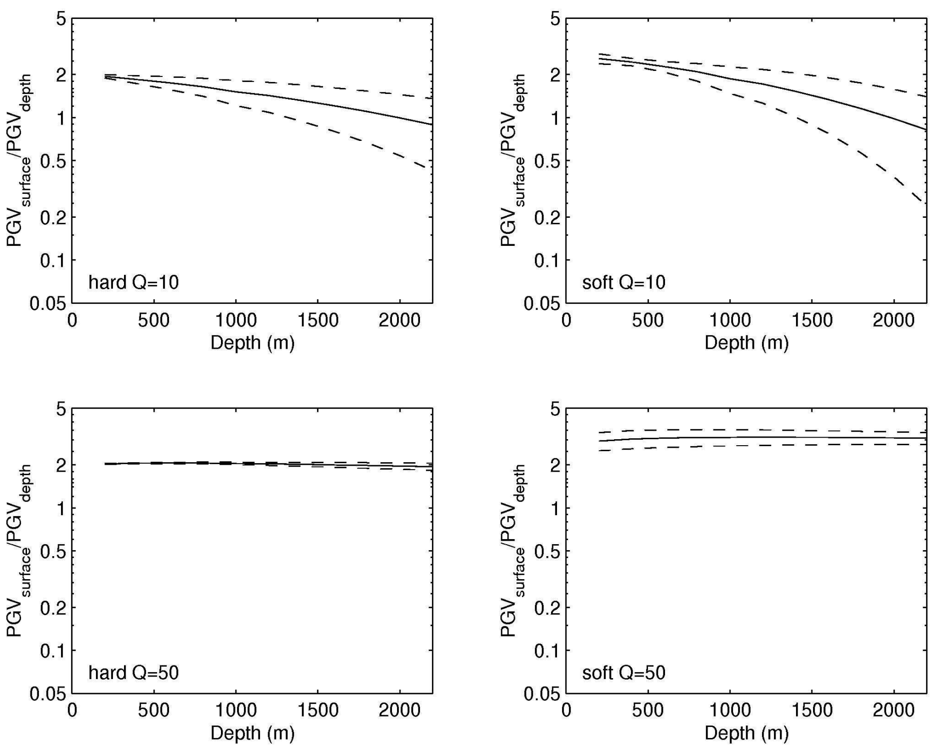

Figure 3. Like Figure 2 for PGV.

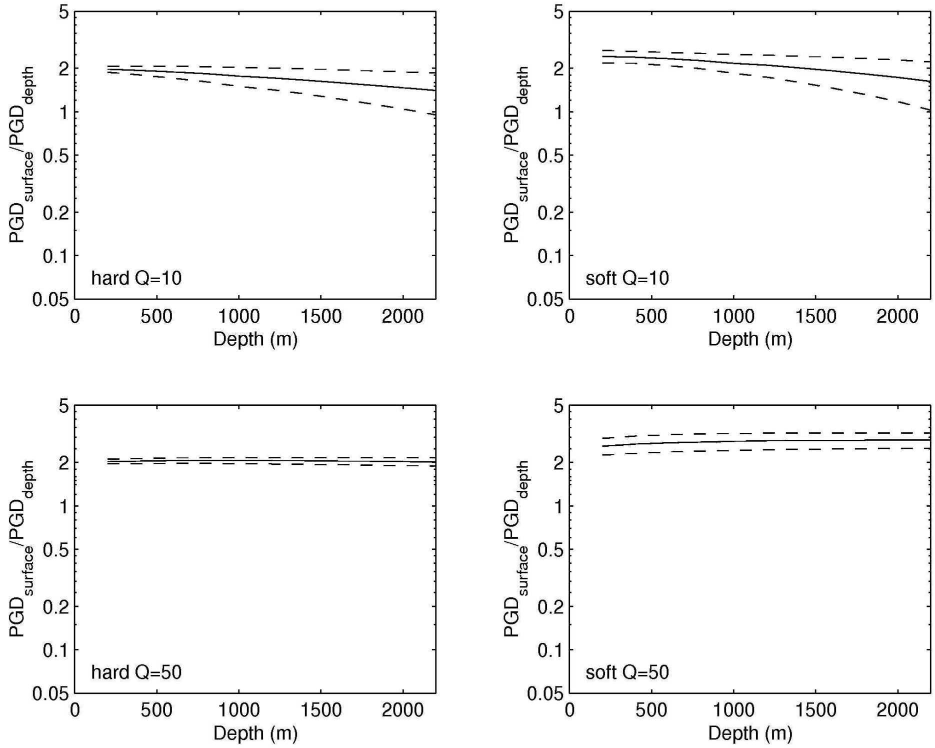

Figure 4. Like Figure 2 for PGD.

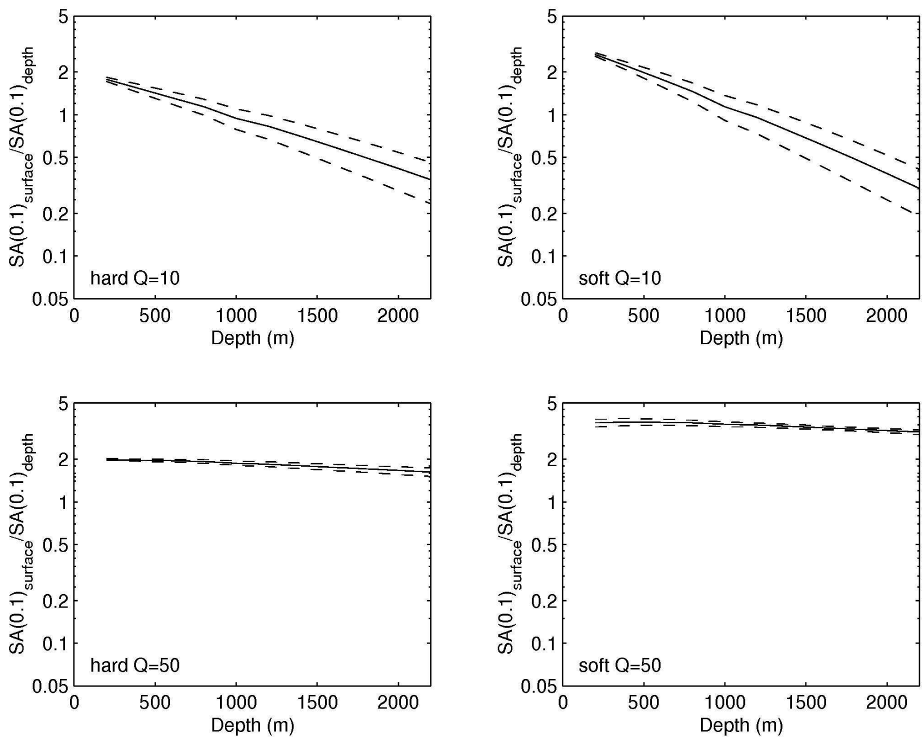

Figure 5. Like Figure 2 for SA at 0.1s.

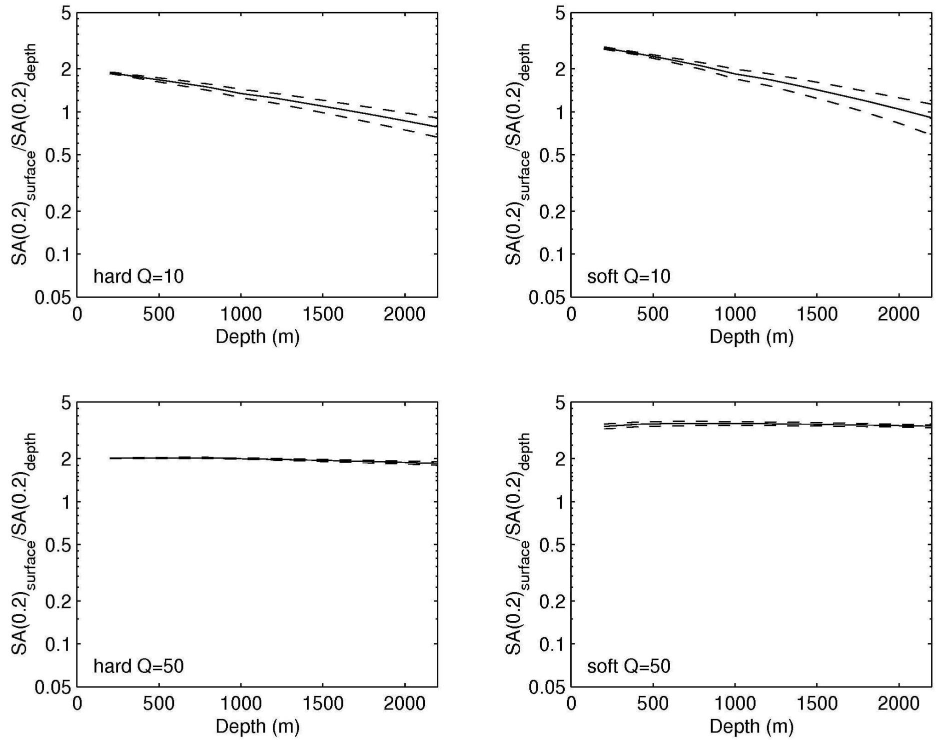

Figure 6. Like Figure 2 for SA at 0.2s.

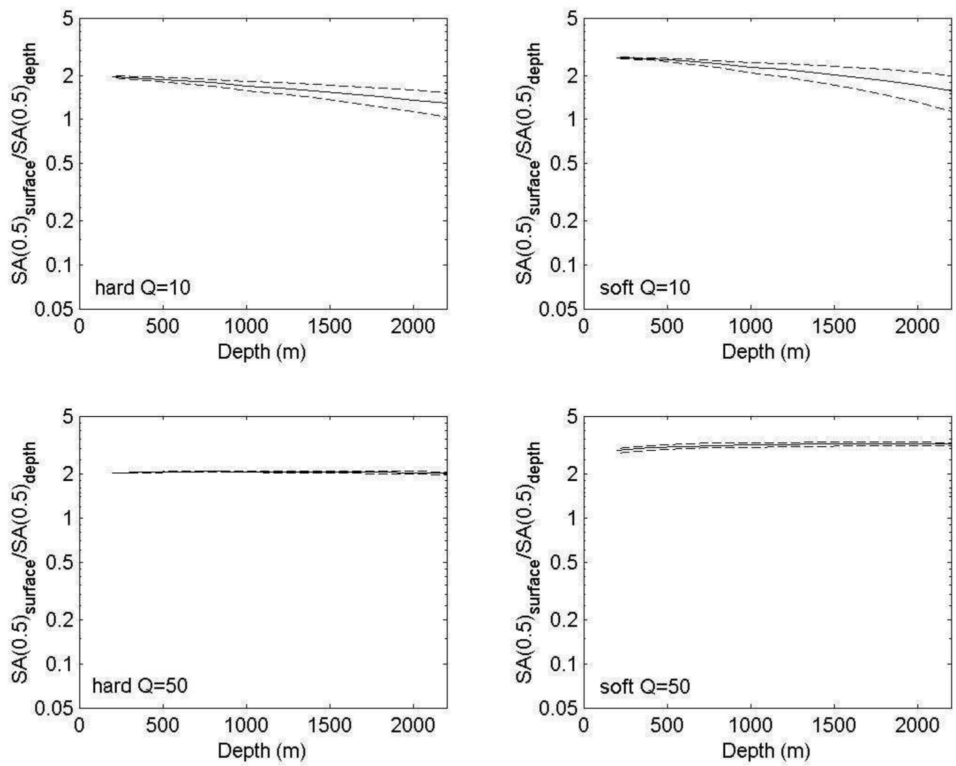

Figure 7. Like Figure 2 for SA at 0.5s.

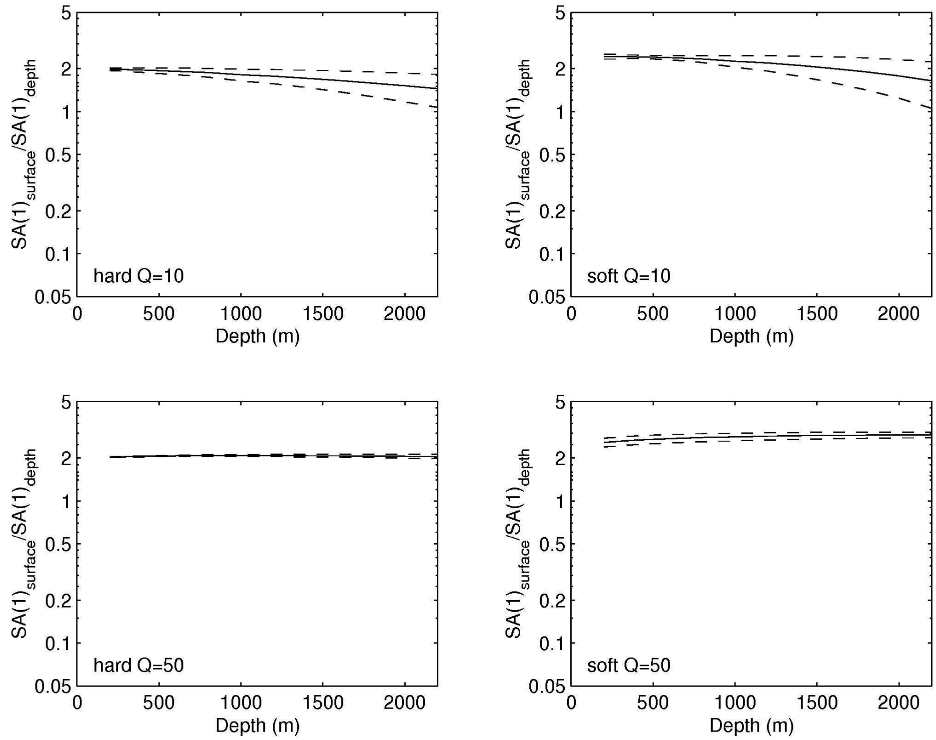

Figure 8. Like Figure 2 for SA at 1.0s.

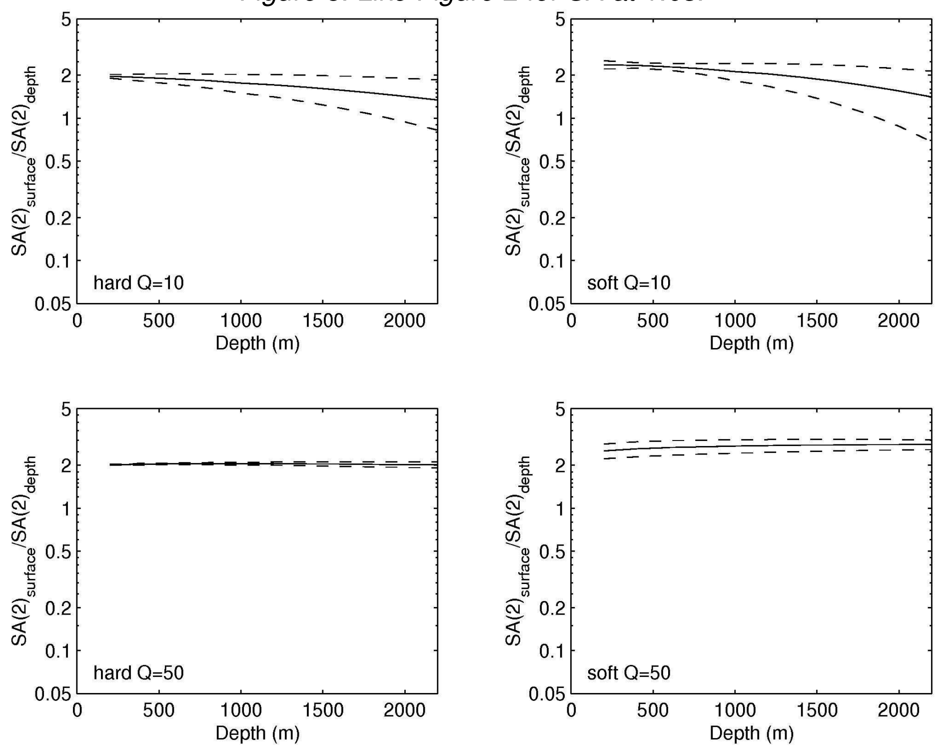

Figure 9. Like Figure 2 for SA at 2.0s.

6. Conclusions

In this short article it is found that strong ground motions at depth are, in general, lower than those on the surface. Also it is found that the estimated ratios do not show much variation with depth except for high-frequency strong-motion parameters for profiles with high attenuation (Q=10) where ground motions at great depths can be higher than those at the surface. However, such a low value of Q is unlikely to occur in practice at depths down to 2km. When details of the near-surface velocity and attenuation structure are not known it is found that the commonly used factor of two (accounting for the effect of the free surface) is a reasonable conservative first estimate at all depths.

7. Acknowledgements

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