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Testing the applicability of correlations between topographic slope and $V_{s,30}$ for Europe

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Abstract

In the past few years a series of articles have been published concerning the use of topographic slope from digital elevation models (DEMs) constructed through remote sensing (satellite imaging) to give first-order estimates of NEHRP site classes based on the average shear-wave velocity in the top 30m, $V_{s,30}$ (Wald and Allen, 2007). We evaluate the potential applicability of these methods taking advantage of a large (706 sites) new database of measured and estimated $V_{s,30}$ values and their topographic slopes for locations in Europe and the Middle East. Novel statistical tests are performed to evaluate the predictive power of the procedure in this region. We evaluate the percentage of sites correctly-classified/misclassified for each site class for active and stable regimes. We also analyze the marginal distributions of the input $V_{s,30}$ and slope values and their impact on the $V_{s,30}$-slope correlations and we evaluate if the method performs better than chance. We also consider the surface geology of sites and investigate whether differences in geology can help explain why certain sites are poorly classified by the method. Finally, we use the city of Thessaloniki (Greece) as a test case for comparison between the results of a recent microzonation and the site classes predicted by $V_{s,30}$-slope correlations.

Our results show that the method does a better job than blind chance for all site classes in active regions but only for class B (rock) and to a lesser extent class C (stiff soil) sites located in stable areas, although the conclusions for stable areas are based on limited data. We recommend that site classifications based on the $V_{s,30}$-slope correlations proposed by Wald and Allen (2007) are only used for regional or national (and not local or site-specific) first-order studies in active parts of Europe and only in the absence of other more detailed information, excluding sites inside small basins or those with special geological conditions that may affect results (e.g. flat-lying volcanic plateaux, carbonate rocks, continental glaciated terrain or a coastal location if slope is not calculated using bathymetric data).

Introduction

Variations in the geotechnical and geophysical properties of near-surface (generally the upper few hundred meters) materials can lead to dramatic differences in earthquake shaking even between adjacent locations. Therefore, it is vital that these potential variations are accounted for within seismic hazard assessments, such as those being conducted by the European Seventh Framework Programme (FP7) project 'Seismic Hazard Harmonization in Europe' (SHARE). It is common to account for local site effects by characterizing locations in terms of their stiffness (often in terms of shear-wave velocity, V_s) of the upper layers at the site. This is the approach adopted in, for example, the European seismic building code Eurocode 8 (EC8), where sites are classified into four categories (D to A in increasing stiffness) by the average V_s down to a depth of 30m ($V_{s,30}$) (other classes are listed in EC8 but these require additional information and they are not considered here) (Comité Européen de Normalisation, 2005). It has been observed (e.g. Borcherdt, 1994) that $V_{s,30}$ is a useful parameter to predict local site amplification in active tectonic regimes (most published justifications of its use mainly concern California). It has limitations for the prediction of amplification for sites underlain by deep sediments, which require knowledge of the geology to depths greater than 30m (e.g. Choi et al., 2005); although Boore et al. (2011) show that $V_{s,30}$ is quite strongly correlated (Pearson correlation coefficients $r \geq 0.6$) with the average V_s down to depths of 600m for Japanese sites.

In spite of the well-known limitations of $V_{s,30}$ as a parameter to predict local site amplification, it has become a de facto standard for seismic hazard assessments at national and international scales, because of its simplicity, use in seismic building codes and the wealth of previous studies supporting its use and correlating $V_{s,30}$ to geological units (e.g. Wills and Silva, 1998) and geotechnical characteristics (e.g. Wei et al., 1996). Actual published measurements of $V_{s,30}$ are rare (mainly due to the high cost of surveys) and are only available at individual locations rather than over wide areas. $V_{s,30}$ can vary considerably even over a dozens of meters and it is still not possible to get a sufficiently dense set of $V_{s,30}$ measurements over a large region. In consequence, for a project such as SHARE that assesses the seismic hazard for the whole of Europe, techniques to estimate $V_{s,30}$ over the entire continent are required. As noted above a number of studies have attempted to correlate $V_{s,30}$ with geological units, which are available via geological maps, at various scales (e.g. for the whole world via the One Geology portal, http://portal.onegeology.org/, last accessed on August 29 2011). Previous studies have noted the large uncertainty in these correlations (e.g. Wills and Silva, 1998). In addition, many of the published studies are for western North America (mainly California) where certain geological units that are common in Europe (e.g. limestone) are not well represented.

In the past few years a series of articles have been published concerning the use of topographic slope from digital elevation models (DEMs) constructed through remote sensing (satellite imaging) to give a first-order estimation of site classes based on $V_{s,30}$ (Allen and Wald, 2007; Wald and Allen, 2007; Allen and Wald, 2009). The basic hypothesis of this method is that basin sediments that generally have low V_s are associated with finer deposits at large distances from mountain fronts, hence, to low gradients, whereas steep slopes are more likely associated to materials with higher V_s (Table 1). Correlations between topographic slopes and site classes are proposed by Wald and Allen (2007) for active tectonic and for stable continental regions in order to derive first-order site-condition maps. It has previously been noted that this method should not be applied in areas dominated by continental glaciated terrain, flat carbonate rocks or recent volcanic plateaux that often have gentle topographic slopes but high V_s (Wald and Allen, 2007). This approach has the benefit of not requiring field-based measurements and it also benefits from the wide and cheap (even free) availability of DEMs. In addition, USGS operate an easy-to-use and free website (http://earthquake.usgs.gov/hazards/apps/vs30/, last accessed on August 29 2011) to obtain site classes (and $V_{s,30}$ estimates) predicted by this approach for the entire globe, which is currently the first website returned by a web search for the keyword 'Vs30'. Consequently, this approach has created much interest (for example, the original article has already been cited over thirty times in journal articles) and it has been used within various recent projects (e.g. Allen et al., 2009). However, this procedure has also led to much debate over the effectiveness of this technique amongst engineering seismologists and geotechnical engineers, much of which is based on a 'feeling' rather than quantitative tests of the method.

Can this rather simple method give realistic first-order information about $V_{s,30}$, whereas near-surface materials can be so heterogeneous? The aim of this article is to compare statistically the correlations proposed by Wald and Allen (2007) to a new large database of measured and estimated $V_{s,30}$ values and their topographic slopes for locations in Europe and the Middle East. The results of such tests will enable an objective decision to be made in the SHARE project, for example, as to whether a European $V_{s,30}$ (or site class) map should be published alongside the probabilistic hazard maps for rock sites, which are currently being computed.

The following section summarizes previous tests undertaken on the applicability of the approach of Wald and Allen (2007) for European sites. Next, the available $V_{s,30}$ measurements and DEM for Europe and the procedure followed in this study are presented. The subsequent section presents the results of the analysis conducted, including novel statistical tests on the predictive power of the technique and an application to Thessaloniki. The article ends with some discussion of the results, conclusions and recommendations.

Previous studies for European sites

The original publications on the method to estimate $V_{s,30}$ from topographic slope (Allen and Wald, 2007; Wald and Allen, 2007) used 43 points from Italy (in addition to many hundreds from California, Taiwan and Utah – i.e. the Italian points are only a small fraction of all data from active regions examined) to help derive correlations between slope and site class for active regions. Allen and Wald (2007) also present histograms comparing the measured and predicted $V_{s,30}$ values for these 43 sites and find a reasonably good correspondence [zero bias but a slightly higher standard deviation, 0.19, compared to existing $V_{s,30}$ site-condition maps, 0.16 – see below for details of how such biases and standard deviations were computed by Allen and Wald (2007)]. As expected, they note the under-prediction of $V_{s,30}$ in the flat-lying Mesozoic shallow-water carbonate and evaporite rocks of Puglia.

Çağnan et al. (2007) compared published site classification maps for Istanbul derived using geological information with those obtained using the Wald and Allen (2007) technique. They find that, in general, the technique works well for NEHRP site class C but they need to modify the slope limits for the different classes to get a better match for other site classes. However, this conclusion is not based on comparisons between measured and predicted $V_{s,30}$ values but simply on visual comparisons of classifications. In addition, no in-situ measurements of $V_{s,30}$ were used, only classes based on geology, which are a crude approximation to true $V_{s,30}$ values. In a related study, Harmandar et al. (2007) qualitatively compare geological maps and $V_{s,30}$ measurements for a handful of sites in Norway and find that the two maps "appear to be well correlated".

Within an application of the ShakeMap methodology to Italy, Michelini et al. (2008) qualitatively compare (their Figure 3) a national site classification map based on geology and one based on the procedure of Wald and Allen (2007). They note a "remarkable correspondence" between the two maps except for the Puglia region. In their application of ShakeMap they decided to use the site classification based on geology.

Recently a French public service project has been completed that tested the applicability of slope-$V_{s,30}$ methodology for thousands of sites in France (Roullé et al., 2010, 2012). They concluded that although the procedure works reasonably well for some zones (e.g. the lower Rhine valley), the $V_{s,30}$ and corresponding amplifications predicted for most areas do not closely match those obtained for the same locations in microzonation studies. They tested DEMs and Digital Terrain Models (DTMs) of various scales and sources and they found that some models gave reasonable results for some locations but not for others.

Hence, no DEM or DTM always gives the best results for a given location. They concluded that slope-$V_{s,30}$ method could at a large scale give "first-order" information where no other data are available. Some of the data collected and used by Roullé et al. (2010, 2012) form one of the sets used here to test the application of the slope-$V_{s,30}$ methodology and correlations for European sites.

Available data and procedure

The strong-motion databank developed in SHARE by Yenier et al. (2010) by combining various strong-motion databases, in addition to some of the French data collated by Roullé et al. (2010, 2012) and Swiss data provided by ETHZ, leads to a set of 516 sites with direct measurements of $V_{s,30}$ (Table 3 and Figure 1), 147 sites with measurements from a nearby site and 43 inferred from detailed site class information (Table). This total of 706 sites are the basis of the analysis presented here. We analyze sites with measured $V_{s,30}$ to avoid additional uncertainties coming from the incorrect classification of site class based on surface geology. Moss (2008) determined that $V_{s,30}$ uncertainties depend on measurements methods (with 1-3% uncertainty for some invasive methods to 20-35% uncertainty for correlations from geological units).

Within SHARE a seismotectonic zonation map was developed for use in selecting appropriate ground-motion prediction equations (GMPEs) for all locations (e.g. those developed for active regions being used in areas defined as active on this map) (Delavaud et al., 2012). Delavaud et al. (2012) used various global and regional databases on geology, tectonics, seismicity and crustal structure and kinematics to classify locations into: active and stable zones, which were used here to choose the appropriate relations of Wald and Allen (2007) between slope and NEHRP class (Figure 1). Some $V_{s,30}$ measurements are located outside the area covered by the zonation of Delavaud et al. (2012), mostly in Iran and Israel, areas we consider as tectonically active (Figure 1). From Table 3 it can be seen that the majority of available slope-site class pairs are from active rather than stable regions, as is unsurprising since most locations are strong-motion stations that have recorded at least one earthquake. Delavaud et al. (2012) split active zones into: dipping slab and deep source, compression and accretion wedge, extension, mixed, strike-slip and transform, spreading ridge, magmatic province and volcanoes; and they further distinguish in the stable zones between: shield, continental and oceanic. These subdivisions were not considered here because Wald and Allen (2007) did not use subdivisions beyond active and stable and, in addition, there are few stations for many of these subdivisions. Future studies may investigate using these subdivisions to improve the correlations between slope and site class. 17% of the European landmass is classified by

Delavaud et al. (2012) as active and the rest as stable. It should be noted, however, that Wald and Allen (2007) developed their relations for stable regions based on measurements from Australia and Memphis, which may correspond more closely to the 'shield' category of Delavaud et al. (2012), for which we have no sites. Our dataset for stable regions is poor, and it is not particularly representative of stable areas Europe-wide (e.g. the vast majority of points are from a few measurement campaigns by BRGM in France).

Table 1 summarizes the correlations between slope and NEHRP site class proposed by Wald and Allen (2007) and Allen and Wald (2009) for active and stable regions. Discrete steps were used to estimate the site class from the slope in this study. The slight modification to the limits of the slope categories introduced by Allen and Wald (2009) does not affect the results obtained here because there are very few NEHRP Class E sites in the observed dataset, for which the lower slope limit was modified by Allen and Wald (2009). Therefore, we only present results using the correlations of Wald and Allen (2007), which we believe are the correlations used by the wider community. In the following sections we generally adopt the NEHRP site classification for consistency with Wald and Allen (2007) even though for future applications in Europe it is likely that the EC8 categories would be used.

The topographic slopes were computed using the global DEM of the Shuttle Radar Topography Mission SRTM30, which has a 30 arcsec resolution. This is the same DEM used by Wald and Allen (2007). Allen and Wald (2009) tested the use of higher resolution DEMs and proposed new slope limits for the classification of sites using these DEMs. They find that although higher resolution DEMs lead to finer site classification maps these maps are not, in fact, more accurate statistically speaking. Based on their analysis for France, Roullé et al. (2010, 2012) concluded similarly on this issue. In this article, we do not test higher resolution DEMs. For consistency with Wald and Allen (2007) we use the grdgradient command of Generic Mapping Tools (GMT) (Wesson and Smith, 1998) to compute the topographic slopes. For easier data manipulation and analysis, we had originally used the Slope tool of ArcGIS (ESRI, 2011), which uses a different algorithm to calculate topographic slopes. GMT's grdgradient uses centered first differences (i.e. the four directly adjacent pixels are used) whereas ArcGIS's Spatial Analyst uses a weighted average of three central differences, which includes the eight neighboring pixels associated with a weighting matrix (Horn, 1981). Furthermore, comparing topographic slope grids calculated by GMT and ArcGIS shows differences due to interpolations and the metric projection introduced by the gridding tools. Comparing the slopes computed using the two approaches (Figure 2) shows that for some sites there are considerable difference in the values, although the predictive power of the Wald and Allen (2007) technique turns out to be similar using the GMT or ArcGIS slopes.

The sites for which both $V_{s,30}$ and slope estimates are available are only a small sample of the complete population of European sites. It is useful to compare these sample distributions with the distributions of the overall population. Obviously for $V_{s,30}$ this cannot be done because $V_{s,30}$ has not been measured for all sites in Europe but the true distribution of slopes in Europe can be approximated by sampling the DEM used here at many locations distributed randomly over the continent. The true distributions of slopes in Europe were estimated by computing slopes at 10 000 random locations. Interestingly the distribution of site classes predicted by converting these slopes to NEHRP class using the limits proposed by Wald and Allen (2007) matches the distribution observed from the locations available for this study quite closely, especially for active regions (Table 3), thereby suggesting that the data used here are representative of European sites. Nevertheless, Figure 3 shows that sites with higher relief are slightly under-represented and those with lower relief are over-represented in the distribution of locations used here (mainly for active regions), which is unsurprising since measurements and instrument installation are difficult in steeper areas and are performed mainly in areas of high seismic risk (i.e. urban areas), which are often located on flat terrain (e.g. valleys, basins or plains).

As argued by Castellaro et al. (2008) in the context of graphs of $V_{s,30}$ against site amplification, logarithmic scales should only be used when data span several orders of magnitude. They also show that using a logarithmic scale when one is not justified can lead to the visual impression of a stronger correlation than if a linear scale is used. For this study, slope ranges over many orders of magnitude [from practically zero with numerous slopes less than 0.001 to 0.637, if those from 50 coastal sites for which the grdgradient approach does not work (see below) are excluded], but not for $V_{s,30}$, which runs from 92 to 3011m/s with most in the range 200 to 500m/s. Therefore, Figure 3 shows the data with a linear $V_{s,30}$ axis rather than the logarithmic $V_{s,30}$ axis used by Wald and Allen (2007), suggesting that the correlation between $V_{s,30}$ and slope is weak. When plotted using a logarithmic $V_{s,30}$ axis and with the addition of the proposed correlations of Wald and Allen (2007) the correlation between $V_{s,30}$ and slope appears stronger (Figure 4). On the other hand, as pointed out by one of our anonymous reviewers, $V_{s,30}$ is roughly lognormally distributed and hence it could be argued that a logarithmic transformation is justified.

From Figure 3 it can be seen that the distributions of $V_{s,30}$ in active and stable regimes are similar whereas the distributions of slope in the two types of regions differ; there is larger percentage of gentle slopes in stable areas (e.g. in the northern plains that stretch from eastern England to Russia) compared to active regions and vice versa for steeper slopes. This similarity in $V_{s,30}$ distributions but differences in slope distributions suggests that the development by Wald and Allen (2007) of separate $V_{s,30}$-slope relations for stable and active regimes was justified and, qualitatively, the difference between the two sets of relations is in the correct direction.

Results

The predictive power of the correlations proposed by Wald and Allen (2007) for the 706 $V_{s,30}$-slope pairs considered here is summarized in Table 4 and Figure 4. It can be seen that for active regions the correlations appear to work quite well but that they do a poor job in predicting classes in stable areas. In the following section we seek to make this qualitative observation more quantitative by applying various statistical techniques.

Because of the considerable difference in the slope limits between active and stable regions for NEHRP class B sites proposed by Wald and Allen (2007) (>0.138 for active but >0.025 for stable zones) when the limits for stable zones are applied to sites from active zones many more class B sites are correctly classified. The consequence of this, however, is that many class C and D sites are incorrectly classified as class B. The outcome of assuming the limits for active zones for all sites is exactly the opposite: an improvement in the classification of class C and D sites but a reduction in the ability to predict class B sites.

Only seeking to distinguish between class C, D or E (roughly corresponding to soil sites), where site amplification is likely, and class B (rock) leads to apparently better results. For example, 85% of class C, D and E sites are correctly classified for active regions but, in fact, 90% of the observed $V_{s,30}$ values are from such sites (and only 10% from class A or B sites) so this apparent improvement may not be real. Table 5 shows the percentage of sites misclassified for each predicted site class. In the artificial-intelligence and machine-learning communities such tables are known as confusion matrices. Note that this table shows different information than Table 4 since Table 5 gives the chance of a predicted site class being correct, e.g. p(true class=B|predicted class=B), whereas Table 4 gives the chance that a observed site class is correctly predicted, e.g. p(predicted class=B|true class=B). Bayes's theorem, e.g. p(true class=B|predicted class=B)=p(predicted class=B|true class=B)p(true class=B)/p(predicted class=B), allows the conversion from one representation to the other. In fact, since the distributions of true site class and site class converted from slope are similar (Table 3) the values reported in Tables 3 and 4 are also comparable. The table for active regimes shows that if a site is predicted as A/B then there is only 26% chance that it actually is A/B. In contrast there is a 62% chance that a site classed as C is actually C.

On Figure 4, despite considerable scatter, a tendency of increasing $V_{s,30}$ with increasing slope is observed. A large number of points, however, do not fall inside the predicting boxes. There are a handful of sites with steep slopes (>0.138 leading to classification as A/B) but low $V_{s,30}$ values (<360m/s, meaning that they are actually class D or E) and, alternatively, gentle slopes (<0.018, leading to a classification as D or E) but high $V_{s,30}$ (>760m/s, meaning that they are really class A/B). Investigating the reasons for these outliers could help identify for which type of situations $V_{s,30}$-slope correlations are unlikely to work. Table 6 lists the sites that are identified as particular outliers in the scatter plot shown on Figure 4. Only outliers within active areas are listed here because, as noted above, the coverage of stable areas is poor. Outliers whose $V_{s,30}$ are associated with steeper slopes than expected seem to be mainly located within small sedimentary basin not seen by the DEM in a mountainous area, associated to a sedimentary lithology (based on a 1:1.5M geological map of Europe, Cassard et al., 2010) and in coastal locations, where bias in the calculation of topographic slopes can be expected (see below). Outliers whose $V_{s,30}$ are associated with shallower slopes than expected are located either on rock outcrops within sedimentary basins, on flat-lying sedimentary rocks (as expected by Wald and Allen, 2007).

Statistical tests of the predictive power of the procedure

The marginal distributions of the input $V_{s,30}$ and slopes are analyzed using histograms of the observations binned into small intervals (Figure 3). These marginal distributions show that the observations come predominantly from sites with $V_{s,30}$ between about 200 and 500m/s, which corresponds to NEHRP classes C and D, and sites with slopes between 0.01 and 0.1m/m, which using the conversion scheme of Wald and Allen (2007) for active tectonic regions also corresponds to NEHRP classes C and D. This coincidence between the marginal distributions suggests that the distribution of available observations could be leading to some of the apparent ability of the procedure to predict the site class from the slope. For example, taken to the extreme: if the slope range for class C were from 0 to 1m/m then every site would be classed as C, which due to the distribution of the underlying data would lead to 51% (see Table 3) of the sites from active zones being correctly classified. To test the predictive power of the Wald and Allen (2007) procedure some statistical tests are presented here. The results obtained will be compared to the percentages of sites correctly classified by this technique (Table 4 and Table 5).

For our statistical tests, we take as a hypothesis that there is no correlation between $V_{s,30}$ and slope and consequently we use the distributions of observed (from $V_{s,30}$ measurements) site classes (Table 3, top) to generate random samples of site classes. For example, for active regions each site has a 10% chance of being class A or B, 51% chance of being class C, 36% of being class D and 3% of being class E. These random classes were then compared to those actually observed and the percentage of successful classifications was calculated. In a bootstrapping exercise, this was repeated 100 000 times to obtain a smooth distribution and stable results. As expected the mean probability of successful classification matches the observed distribution of site classes in the sample but there is a scatter around this mean value. Visually this scatter appears to follow a normal distribution. Therefore, the null hypothesis that the scatter obeys the normal distribution was examined using the Kuiper test (Press et al., 1994), which leads us to reject the null hypothesis at the 5% significance level. Examining the scatter using normal probability plots shows that the scatter deviates from the normal distribution at the upper and lower tails. Lacking an explicit statistical distribution as a basis of the analysis, we used the empirical distributions to compute the probabilities of exceeding a given threshold (in this case the observed predictive power of the Wald and Allen technique, Table 4). These probabilities give the likelihoods of obtaining the observed predictive power by pure chance. The distributions are presented in Figure 5. For active regions this analysis shows that the technique of Wald and Allen (2007) is significantly better than chance (less than 0.001% for A/B and C and less than 2% for D) for all site classes, although the method is worse than chance when C, D and E sites are grouped together. For stable regions, the technique is significantly better than chance for Class A/B sites (rock) but not for other site classes. Random generation of site classes using the distribution of site classes obtained by converting slopes to classes using Wald and Allen's limits leads to similar results because of the proximity between the distributions of site and slope-converted-to-site classes (Table 3).

In this article we concentrate on the prediction of site classes rather than actual $V_{s,30}$ estimates for three principal reasons: a) this is the main aim of the procedure proposed by Wald and Allen (2007), b) for many uses at the regional scale a site class would be sufficient and c) just providing a site class rather than a numerical value more clearly demonstrates the uncertainty in the estimation (estimating a $V_{s,30}$ could give a false impression of accuracy). On the other hand, a major advantage of $V_{s,30}$ over site classes is that it is continuous and hence its use does not lead to jumps in predicted site amplification at the edges of site classes. For comparison with Figure 3 of Wald and Allen (2007), showing histograms of the logarithm of the ratio between observed to predicted $V_{s,30}$ values, we estimated actual $V_{s,30}$ values for the 706 sites. This was done using both the procedure of Wald and Allen (2007), i.e. the median $V_{s,30}$ of the limits of the subdivided NEHRP boundaries, and the method of Allen and Wald (2009), i.e. the interpolated $V_{s,30}$ from subdivided NEHRP boundaries. The two approaches gave comparable results so we only present those using the median $V_{s,30}$. Figure 6 presents the obtained histograms for active and stable regions for comparison with those presented on Figure 3 of Wald and Allen (2007). The overall bias is almost zero showing that the procedure does not systematically over- or under-estimate $V_{s,30}$. The computed standard deviation for active regions (0.221) is higher than that reported by Wald and Allen (2007) for California (0.15), which suggests that this procedure: i) does a poorer job in Europe and the Middle East than in California, ii) the $V_{s,30}$ limits are not optimal for our region, or iii) that sites in Europe are more heterogeneous than those in California. The standard deviation for stable regions (0.241) is much larger than that reported for Memphis (0.13) by Wald and Allen (2007) and for Australia (0.19) reported by Allen and Wald (2007), again suggesting that the technique is performing poorly for our data.

The problem with examining histograms such as Figure 6 is that they mainly reflect the underlying $V_{s,30}$ distribution, which is dominated by sites with $V_{s,30}$ between 200 and 500m/s. Therefore, like with the prediction of site classes discussed above, a simple prediction of $V_{s,30}$ equal to the average $V_{s,30}$ of the observations leads to similar results. This is demonstrated in Figure 7 where the expected $V_{s,30}$ assuming a lognormal $V_{s,30}$ distribution for active (426m/s) and stable (424m/s) regions is assumed for every site thereby leading to zero bias and very similar standard deviations to that obtained by the $V_{s,30}$-slope correlations for active regions and actually lower than that obtained for stable regions, although the statistical distributions are not as smooth nor as symmetrical. This example demonstrates that such statistical tools are not useful in examining whether the slope-based procedure is better than chance.

Using lithography to classify sites

Before the advent of the method of Wald and Allen (2007) rapid site classification for large zones was often performed using geological maps (e.g. Bossu et al., 2000). Thanks to projects such as OneGeology it is now possible to freely access geological maps online and, therefore, it may be possible to improve the predictive power of the $V_{s,30}$-slope approach by combining it with geological information. To investigate further the influence of geology on the correlations between $V_{s,30}$ and slope, all sites used here have been classified into broad lithological classes using a 1:1.5M geological map of Europe provided by D. Cassard (Figure 4). On this figure, the lighter the blue the softer the lithology (typically, dark blue corresponds to rock such as granite whereas sediments are shown as light blue). Gentle slopes are often associated with softer soil. This is a first-order confirmation of Wald and Allen's hypothesis about $V_{s,30}$-slope correlations.

Lithological class information could be useful in two ways. Firstly, if a site was classified as belonging to a certain lithological unit then the user could be warned against using the $V_{s,30}$-slope approach. For example, Wald and Allen (2007) themselves note that the technique is unlikely to work for flat-lying limestone (e.g. Puglia in Italy) or volcanic plateaux (e.g. the south lowlands of Iceland) because despite being relatively flat they should be classes as NEHRP B (or even A). Volcanic terrain and carbonate rocks are identified in pink and red on Figure 4. Most of these points belong to the cloud of points, except for a few outliers. For example, one $V_{s,30}$ value associated to volcanic lithology is much larger than predicted by the $V_{s,30}$-slope correlation for stable regions. Despite some outliers, no general tendency of much higher $V_{s,30}$ than expected is observed. Secondly, lithological information could be used to develop individual $V_{s,30}$-slope correlations for different geological formations or even $V_{s,30}$-lithology correlations directly like those of Wills and Silva (1998). This possibility is not investigated here.

Thessaloniki

In urban areas within seismically-active parts of Europe it is quite common to undertake seismic microzonation studies to identify the expected site amplification, due to variations in lithology and topography, in different zones of a town or city. These microzonations, e.g. the study by Bernardie et al. (2006) for Lourdes (France), are generally based on field measurements (e.g. horizontal-to-vertical, H/V, microtremor recordings) combined with local geological maps and soil and, if available, shear-wave profiles. To cover a large urban area takes many months and much effort. Therefore, methods based on information available from remote-sensing data (in this case topographic slope) are attractive in their apparent ability to provide first-order information on site classes very rapidly. As an example, we have chosen the city of Thessaloniki (Greece) as a test case for comparison between the results of a recent microzonation, which was based on geophysical measurements, local geology, H/V measurements and damage patterns of the 1978 damaging earthquake, (Theodulidis et al., 2006) and the site classes predicted by the $V_{s,30}$-slope correlations of Wald and Allen (2007). The results of this comparison are shown in Figure 8 using both grdgradient of GMT and the Slope tool of ArcGIS. Other microzonations exist for Thessaloniki, for example that by Anastasiadis et al. (2001) used by Pitilakis et al. (2006) for risk scenarios, which shows significant differences to the map of Theodulidis et al. (2006).

From Figure 8 it seems that the largest errors in site class estimation (red and dark blue squares, i.e. 7% of tested area) are those associated with coastal locations. Site classes for 42% of the area are well predicted whereas 14% and 37% are respectively under and over-estimated by a single class. The software routine used in the approach of Wald and Allen (2007) (grdgradient of GMT) calculates the maximum rate of change between each cell and its neighbors. Therefore, since sea level elevation is set to zero the slope estimated for coastal cells could be underestimated. Wald and Allen's method classifies most of coastal cells as NEHRP B soil class (i.e. because of the proximity of the sea considered as the boundary of DEM grid) where the microzonation map predicts class D or class C sites. In addition, classification based on

Wald and Allen (2007) do not indicate the area of class B (rock) sites (dark green) at the east of the urban area that microzonation does. From Figure 8, results are shown using ArcGIS's slope calculations. It seems that results are better for Thessaloniki using this software: the coastal cells are not systematically badly estimated (because of the different slope calculation algorithm) and it detects a narrow area of class B at the east of the city. The method is, therefore, reasonably good at identifying class D sites.

Discussion

Wald and Allen (2007) proposed topographic slope as a proxy for site classifications. They suggested it could give a first-order estimate of $V_{s,30}$ associated with large uncertainty where no detailed geological maps are available. For the data from Europe considered here, a tendency of increasing $V_{s,30}$ with increasing slope is observed. Nevertheless, at least four factors may explain the large scatter of this correlation observed on Figure 4, which are discussed in the following paragraphs.

We checked why some points were particularly badly estimated (Table 6). Problems were mainly due to sites in sedimentary basins whose dimensions are too small to feature in SRTM30 (i.e. spatial resolution around 1km) and to coastal sites for which slope calculation is biased due to boundary conditions of the DEM. Some finer DEM could be used (e.g. SRTM3 from NASA/USGS with a spatial resolution of 90m). Topographic slope is a local measure depending on the resolution of the DEM used (the higher the resolution the higher the local slope). Changing the spatial resolution of DEM means that the correlations between slope and $V_{s,30}$ must also be modified. Allen and Wald (2009) used a 9 arcsec DEM which recovers finer-scale variations of the terrain but introduces more noise. They do not find improved results with respect to the 30-arcsec DEM and suggested that larger resolution (SRTM30) could provide more stable $V_{s,30}$ estimates. Furthermore, Roullé et al (2012) tested DEMs and DTMs of various scales and sources and they found no clear or systematic improvement of results with better resolutions. In conclusion, small topographic heterogeneity cannot be well represented by slopes calculated from SRTM30, but it seems that higher-resolution DEMs may not improve results but only lead to noisy slope estimations (e.g. due to the canopy or local heterogeneities).

Comparing site classes estimated using the procedure of Wald and Allen (2007) with those determined in a detailed microzonation (Theodulidis et al., 2006) shows that, for this example, slopes are underestimated close to water surfaces and that class B sites were misclassified. Either cells close to water should not be considered or a DEM combining bathymetric and topographic data should be used.

The geological map used here to classify sites is at a Europe-wide scale. Each $V_{s,30}$ measurement is associated to lithological class using this map. It is obvious that large uncertainties are associated with such associations because it does not take into account small geological heterogeneities. Whereas it was expected that softer soil would be associated with shallower slopes on Figure 4, a large scatter was observed. Furthermore, it seems that we do not have sufficient data for volcanic plateaux or flat-lying carbonate rocks. Wald and Allen (2007) suggested that for such terrain, $V_{s,30}$ estimated from slope would be underestimated. We observed more outliers than Wald and Allen (2007) probably because SRTM30 cannot resolve small basins in mountainous regions, which are common in Europe.

Furthermore, the type of international database of geophysical parameters used here can be heterogeneous due to various measurement techniques. This could be a reason for some of the scatter seen on Figure 4. For example, the quality of very high $V_{s,30}$ measurements (>1500m/s) and the correctness of the procedures used to derive those values may be questionable because of the effect of rock weathering. It would be of great interest to obtain more $V_{s,30}$ measurements to improve our analysis but such measurements are expensive, difficult and time-consuming.

Our aim here was not to propose new correlations between slope and $V_{s,30}$, especially since we do not believe our dataset is sufficient to do so, but to statistically test the correlations published by Wald and Allen (2007), which are commonly used. Is the method better than chance? It seems to do a better job than blind chance for active regions but not for stable areas (except in identifying class A/B sites). For European stable regions, we currently suggest that the Wald and Allen (2007) method should not been applied. Our results, admittedly based on limited data mainly from France, suggest that the procedure of Wald and Allen (2007) is not better than chance at correctly classifying sites. This could be because of differences in stable regions in Europe and those considered by Wald and Allen (2007), which were generally shields (e.g. Australia). Wald and Allen's method should only be used for regional or national first-order studies in active regions where no other information is available.

One of the major factors contributing to the popularity of the Wald and Allen (2007) technique is the relatively ease with which the topographic slope can be evaluated. Other techniques to assess site classes based on DEMs have been published (e.g. Iwahashi et al., 2010; Oye et al., 2008), which can account for more details of the geomorphology or topography (e.g. surface texture, openness or altitude) or more complex analysis methods (e.g. integrated imaging analysis methods, Yong et al., 2008) but require more complex computations. Roullé et al. (2010, 2012) have tested some of these approaches but find that their additional complexity does not necessarily lead to better results. Furthermore, although $V_{s,30}$ is a commonly-used parameter, there are still doubts on its capacity to be an indicator of site amplification (e.g. Castellaro et al., 2008). Phenomena involved are sometimes too complex to be completely captured by this proxy (e.g. it gives no indication of the depth of basins). In addition to methods for the prediction of $V_{s,30}$ from topographic parameters, some researchers (e.g. Bungum et al., 2007) have sought to develop correlations to predict other indicators of site conditions (e.g. depth to bedrock). Piltz et al. (2010) compared a site class map derived using ambient-noise measurements to a map developed using the method of Wald and Allen (2007) and they observed a better correlation between $V_{s,30}$ and the local geology than between $V_{s,30}$ and slope. It should be noted, however, that the $V_{s,30}$ estimates they used were calculated mostly by inversion of H/V curves from ambient-noise measurements, which are associated with large uncertainties. As discussed recently by Thompson et al. (2011), spatial coverage and accuracy are inversely correlated and the different site-response proxies should be combined to take advantage of the inherent benefits of each method when mapping site response. For example, Thompson et al. (2011) suggest that where velocity profiles are unavailable, the Wald and Allen (2007) method outperforms surficial geology in estimating site amplification for short structural periods, but geology outperforms $V_{s,30}$-slope correlations at longer periods. Wald et al. (2011) proposed a hierarchical approach including topographic slope, geological maps and $V_{s,30}$ observations to derive $V_{s,30}$ maps.

Conclusions and recommendations

In this article we have statistically tested the $V_{s,30}$-slope (or more specifically the NEHRP class-slope) correlations published by Wald and Allen (2007) for Europe and parts of the Middle East. In total 706 sites with $V_{s,30}$ measurements were used. It is found that the technique leads to a site classification that is better than chance for all NEHRP site classes in active areas. For stable areas, there are still limited data to enable firm conclusions but our results suggest that the proposed correlations perform poorly in these zones.

Based on our findings we reiterate the recommendations of Wald and Allen (2007) that site classifications based on $V_{s,30}$-slope correlations should only be used for regional or national (and not local or site-specific) first-order studies. In addition, they are only to be used in the absence of other more detailed information (e.g. microzonation studies) and not for sites inside small, relative to the DEM resolution, basins or those with special geological conditions that may affect results (e.g. flat-lying volcanic plateaux, carbonate rocks, glaciated continental terrain or coastal pixels if the slope is not calculated using bathymetric data). Again many of these limitations were stated by Wald and Allen (2007). Site classifications based on $V_{s,30}$-slope correlations are not sufficiently accurate to replace actual field measurements and they should not be used for site-specific studies. Consequences of erroneous estimation could be serious, so the user of such correlations should be aware that they only provide a first approximation and the true site class for a given site could be incorrect by one or, even, two classes (in either direction). At a local scale, further investigations should be carried out based on geology and measurements. In addition, the slope limits used for estimating $V_{s,30}$ are dependent on the slope-calculation algorithm and, as previously shown by Allen and Wald (2009) and Roullé et al. (2010, 2012), on the DEM resolution.

We prefer predicting a site class rather than $V_{s,30}$ even when this is associated with a (large) standard deviation because we believe it gives a better indication that the site class is only an estimate and is not based on a measured $V_{s,30}$ value. We fear that the reporting of a numerical estimate for $V_{s,30}$ with a measure of its uncertainty would lead to the temptation to use the value and forget about the scatter.

Data and resources

The $V_{s,30}$ data used in this study was mainly obtained from the SHARE strong-motion database (Yenier et al., 2010), which was compiled from various public sources. It is planned that the database will be made public by SHARE or a subsequent project in the coming months. $V_{s,30}$ values for some Swiss sites were provided by Donat Fäh and Valerio Poggi from ETHZ. French sites were taken from various BRGM research or commercial studies, which cannot be made public. Topographic slopes were computed using the grdgradient routine of Generic Mapping Tools (Wessel and Smith, 1998) unless otherwise stated [ArcGIS's slope tools (EPRI, 2011) are used for some comparisons] from the SRTM30 DEM, which is publically available (http://www.src.com/datasets/datasets_terrain.html#SRTM30_GTOPO30_DATA, last accessed on August 29 2011). The 1:1.5M European geological map was extracted from the GIS provided by the Mineral Resources Division of BRGM (Cassard et al., 2010). Nikos Theodulidis provided the GIS files of the microzonation map of Theodulidis et al. (2006).

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Tables

Table 1: Ranges of topographic slopes proposed by Wald and Allen (2007) and Allen and Wald (2009) for classification of sites into NEHRP categories. Also given is the approximate correspondence between the NEHRP and EC8 categories. Note that Wald and Allen (2007) subdivided the NEHRP class C and D into three subclasses - these subclasses are not considered here except for the construction of the histograms shown in Figures 6 and 7. EC8 also features a category E (shallow soil sites over rock) but this requires knowledge of the depth to bedrock, which Wald and Allen (2007) did not seek to predict.

NEHRP Class	$V_{s,30}$ range	Roughly Equivalent EC8 class	Slope range (m/m)		
			Active tectonic (Wald and Allen, 2007)	Active tectonic (Allen and Wald, 2009)	Stable continental (Wald and Allen, 2007)
A/B	>760m/s	A	>0.138	>0.14	>0.025
C	360-760m/s	B	0.018-0.138	0.018-0.14	0.0072-0.025
D	180-360m/s	C	0.0001-0.018	0.0003-0.018	2×10^{-5}-0.0072
E	<180m/s	D	<0.0001	<0.0003	$<2\times10^{-5}$

Table 2 : Types of $V_{s,30}$ measurements used in this study. In-situ measurement method can be, for example, SASW, MASW, down-hole or cross-hole, but we do not have this information for all in-situ measurements and hence additional details cannot be given here.

In-situ measurement (exploration depth>30m)	415
In-situ measurement (exploration depth<30m)	101
Inferred from Vs measurement of a close site	147
Inferred from Geomatrix site class (from NGA)	43

Table 3: Percentage of observations in each NEHRP class, topographic slope class and seismotectonic category. Comparison with slopes dataset from 10 000 computed random locations.

From $V_{s,30}$ measurements						
Tectonic regime	Class A/B	Class C	Class D	Class E	Class C, D or E	Total
Active	10	51	36	3	90	574
Stable	15	39	45	1	85	132
Combined	11	49	38	3	89	706
By conversion of measured slope to estimated site class						
Tectonic regime	Slope class A/B	Slope class C	Slope class D	Slope class E	Slope class C, D or E	Total
Active						
Actual sites	18	52	29	2	82	574
Random locations	27	50	18	5	73	1703
Random locations (all as active)	9	36	50	5	91	10 000
Stable						
Actual sites	25	50	23	2	75	132
Random locations	30	36	30	5	70	8 297
Random locations (all as stable)	37	32	27	5	63	10 000

Table 4: Percentage of sites correctly classified using the procedure of Wald and Allen (2007). This table gives the percentage chance that if a site is classed A/B based on its observed $V_{s,30}$, for example, then it is also classed as A/B based on its slope.

Tectonic regime	Class A/B %	Class C %	Class D %	Class E %	Class C, D or E
Active	47	62	43	0	85
Stable	40	45	22	0	78
All as active	35	57	49	0	87
All as stable	77	23	21	0	48

Table 5: Percentage of sites correctly-classified/misclassified for each site class for active (left) and stable (right) regimes. The way to read this table is that if a site is predicted to be class A/B, for example, based on its slope then the rows give the percentage chance that the site is actually class A/B (26%), C (45%), D (26%) or E (2%) for active regions. This is different than shown in Table 4 – it is a more useful measure of the quality of the class prediction given by the technique of Wald and Allen (2007). Note that some of the columns do not sum to 100% because of rounding.

Active

	Predicted class			
Observed class	A/B	C	D	E
A/B	**26**	9	2	0
C	45	**62**	39	10
D	26	27	**54**	90
E	2	2	6	**0**

Stable

	Predicted class			
Observed class	A/B	C	D	E
A/B	**24**	15	6	0
C	39	**35**	48	0
D	36	50	**42**	100
E	0	0	3	**0**

Table 6: Sites with steep slopes (>0.138) but actually classed as D ($V_{s,30}$<360m/s) (top of table) and sites with gentle slopes (<0.018) but actually classed as B ($V_{s,30}$>760m/s) (bottom of table), i.e. the classification of these sites is wrong by two classes. Those slopes in italics are from coastal sites for which the grdgradient routine in conjunction with the resolution of the DEM used completely fails to compute a realistic slope. $V_{s,30}$s are reported to three significant figures for consistency with original sources of these values and with plots shown here, even though two significant figures may be more appropriate given the experimental uncertainties in such values.

Location	$V_{s,30}$ (m/s)	Slope (m/m)	Possible reason for misclassification
Ambarli (Turkey)	173	29.923	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Antalya Finike Meteoroloji Istasyon Mudurlugu (Turkey)	299	0.213	Coastal site, slope is over-estimated because calculation does not take into account bathymetric values
Bolu Goynuk Goynuk Devlet Hastanesi	348	0.138	Lithology probably associated to a small sedimentary basin in a mountainous area not seen by the DEM
Bolu Mudurnu Ptt Binasi (Turkey)	355	0.260	Lithology probably associated to a small sedimentary basin in a mountainous area not seen by the DEM
Botas-Gas Terminal (Turkey)	275	49.731	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Burdur Merkez Bayindirlik Ve Iskan Mudurlugu (Turkey)	294	0.166	Sedimentary lithology, along a lake, not seen by the DEM in a mountainous area
Debar-Skupstina Opstine (Macedonia)	175	0.256	Sedimentary lithology, along a lake, not seen by the DEM in a mountainous area and unknown origin of $V_{s,30}$ value
Gachsar (Iran)	275	0.456	$V_{s,30}$ not measured but inferred from other information
Gemona-Scugelars (Italy)	240	0.309	Sands and gravels; close to the limit of a small basin; $V_{s,30}$ inferred from Vs measurement of an adjacent site
Grenoble - (France)	308	0.193	Within small sedimentary basin in a mountainous area not seen by the DEM
Iri (Georgia)	275	0.169	$V_{s,30}$ not measured but inferred from other information
Istanbul-K.M.Pasa	339	29.943	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Istanbul-Zeytinburn (Turkey)	230	49.725	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Izmir Dikili Meteoroloji Istasyon Mudurlugu (Turkey)	193	48.803	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Kicevo-Skup Op. (Macedonia)	250	0.200	At the border of a small sedimentary basin in a mountainous area not seen by the DEM; $V_{s,30}$ inferred from Vs measurement of an adjacent site
Korinthos-Town Hall	345	29.938	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Lefkada-Hospital (Greece)	258	29.967	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Lefkada-OTE Building (Greece)	207	48.756	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Lepena (Slovenia)	229	0.637	Within small sedimentary basin in a mountainous area not seen by the DEM; $V_{s,30}$ inferred from Vs measurement of an adjacent site
Lourdes - microzonation measurement (France)	293	0.207	Within small sedimentary basin in a mountainous area not seen by the DEM
Mostar-Zavod Za Urbanizam (Bosnia Herzegovina)	350	0.314	Within small sedimentary basin in a mountainous area not seen by the DEM; $V_{s,30}$ inferred from V_s measurement of an adjacent site

Mugla Fethiye Meteoroloji Istasyon Mudurlugu (Turkey)	248	47.862	Site located offshore because of DEM resolution.
Sakarya Karadere Koyu (Turkey)	316	0.235	Sedimentary lithology; low resolution of DEM;
Tekirdag Marmara Ereglisi Kaymakamlik Binasi (Turkey)	325	29.967	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Tonekabun (Iran)	209	35.348	Site located offshore because of DEM resolution.
Veliki Ston-F-Ka Soli (Croatia)	200	0.150	Sediments within sharp topographic features. Inferred from $V_{s,30}$ measurement of a close site.
Yarimca (Turkey)	297	49.612	Coastal site pixel, slope is considerably over-estimated because calculation does not take into account bathymetric values.
Zakynthos-OTE Building (Greece)	235	0.140	Coastal site, slope is over-estimated because calculation does not take into account bathymetric values
Zemo Bari (Georgia)	275	0.191	Within small sedimentary basin in a mountainous area not seen by the DEM; $V_{s,30}$ not measured but inferred from other information
Titograd-Seismoloska Stanica (Montenegro)	900	0.007	On a rock outcrop within a sedimentary basin
Lourdes – microzonation measurement (France)	982	0.012	On a rock outcrop within a sedimentary basin
Tabas (Iran)	767	0.017	Flat-lying sedimentary rocks

Figures

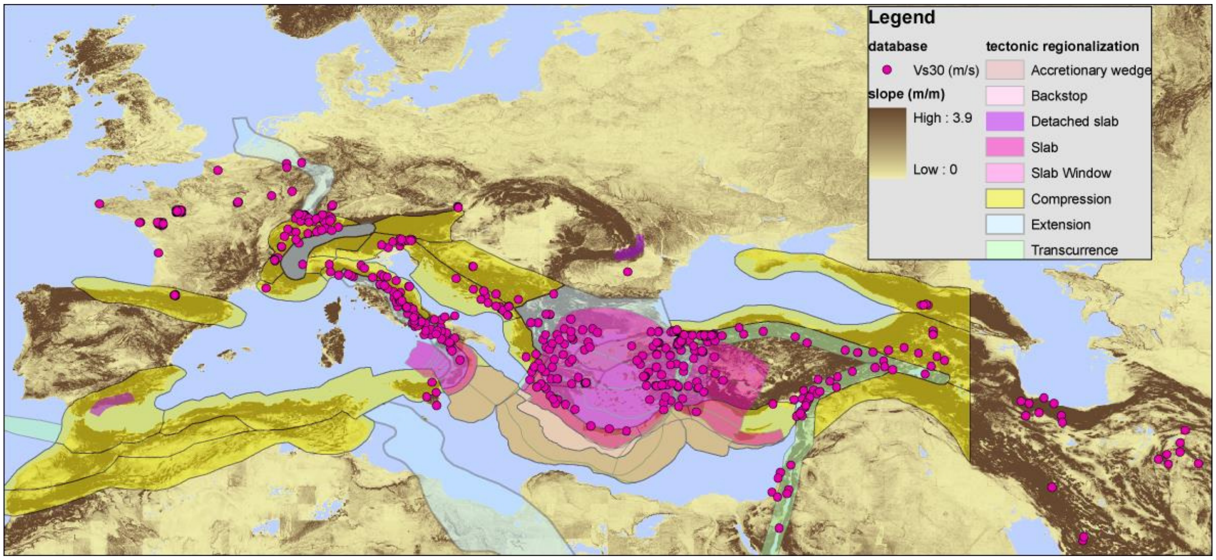


Figure 1: Map of Europe, the Mediterranean and the Middle East showing the seismotectonic zonation proposed by SHARE (Delavaud et al., 2012), the locations of measurements used here and calculated slopes using the SRTM30 DEM.

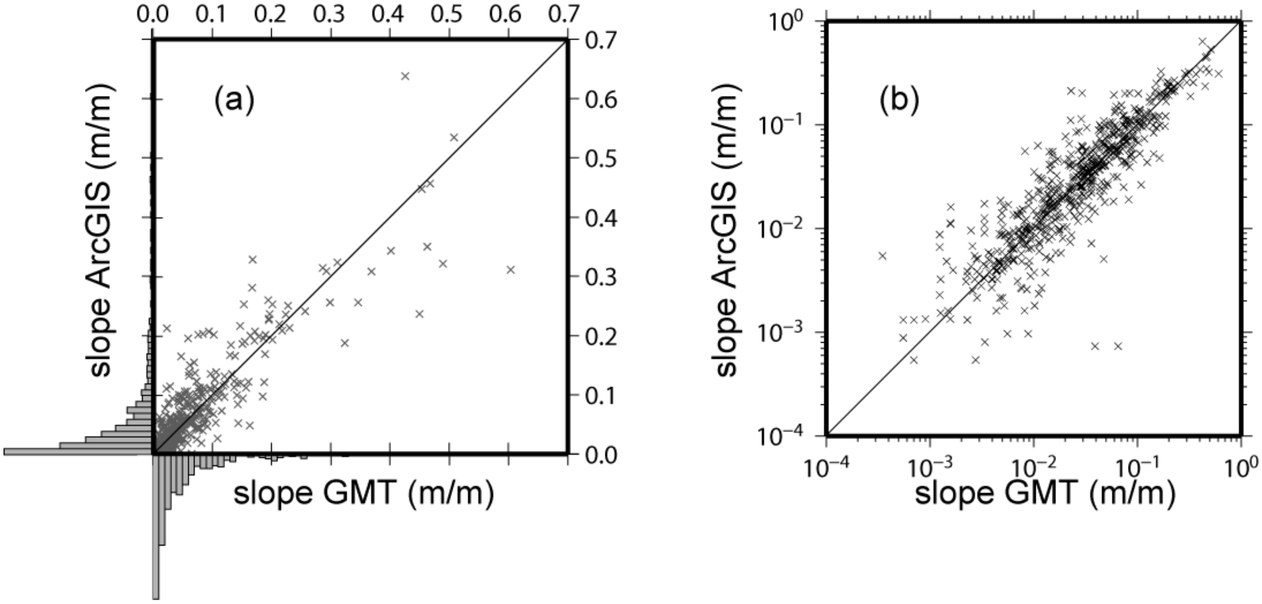


Figure 2: Comparison between the topographic slopes computed using the grdgradient command of GMT and the Slope tool of ArcGIS using the SRTM30 DEM for the 706 sites considered here using a) linear axes and b) logarithmic axes.

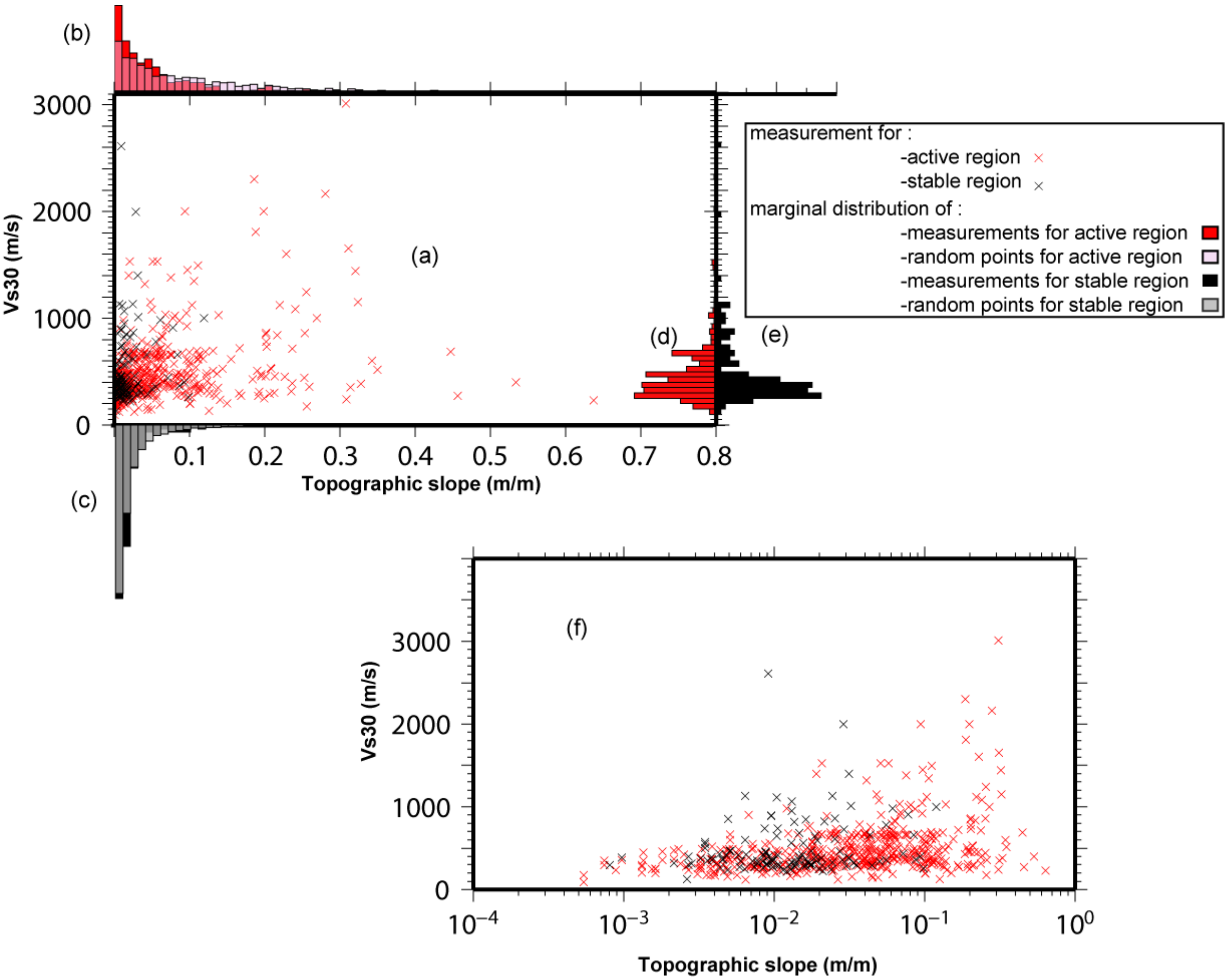


Figure 3: Distribution of $V_{s,30}$-slope pairs used in this study (a). (b) and c): marginal distributions of the slopes respectively for active and stable regions (including the true distribution obtained from 10 000 random locations distributed throughout Europe). (d) and (e): marginal distribution of $V_{s,30}$ values respectively for active and stable regions. (f) : same as (a) but with a logarithmic slope axis.

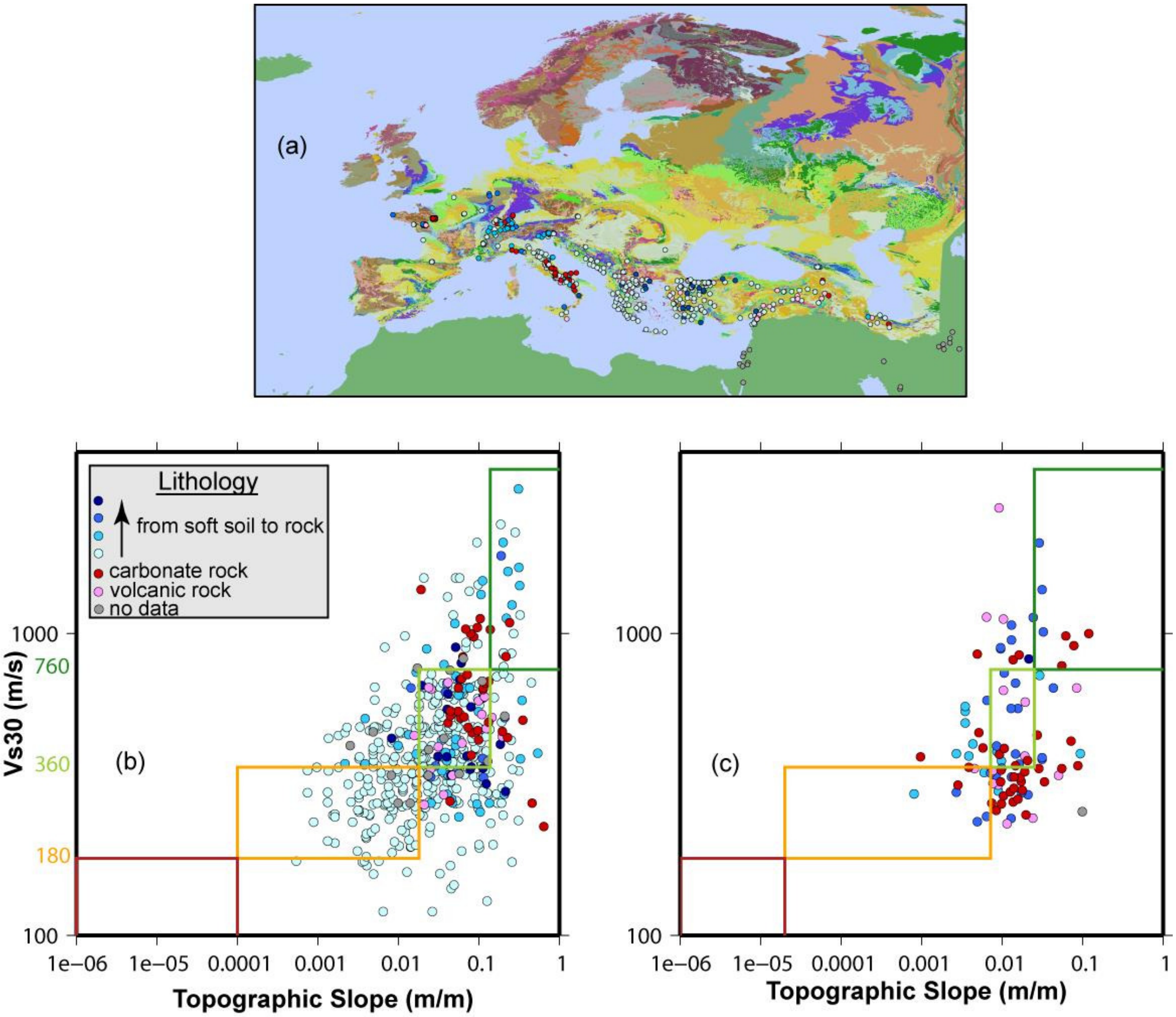
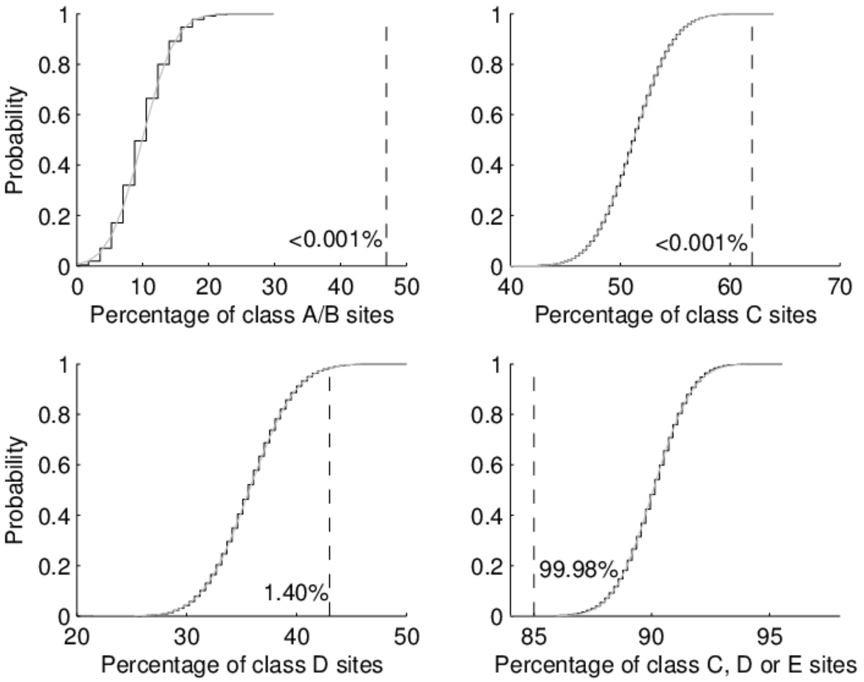
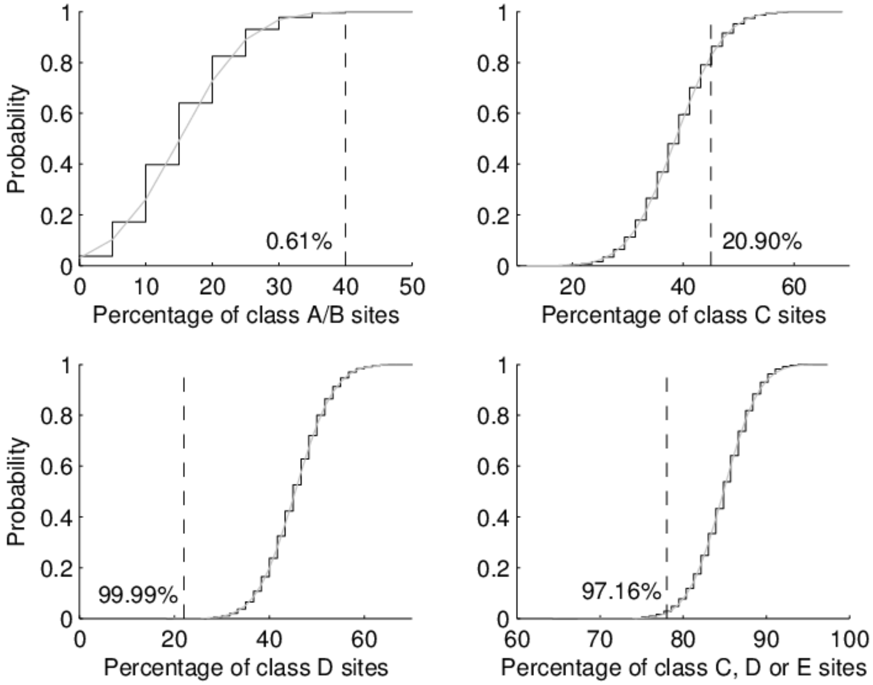


Figure 4: European geological map, distribution of $V_{s,30}$-slope pairs for active and stable regions used in this study and the site class-slope correlations proposed by Wald and Allen (2007) as colored boxes.



a) active



b) stable

Figure 5: Distributions of percentage of sites classified by chance into different NEHRP classes (black lines). Also shown are the fitted normal distributions (gray lines), the observed predictive power of the Wald and Allen (2007) technique (vertical dashed lines) and the chance of surpassing this threshold based on the empirical distribution. a) for active regions and b) for stable regions.

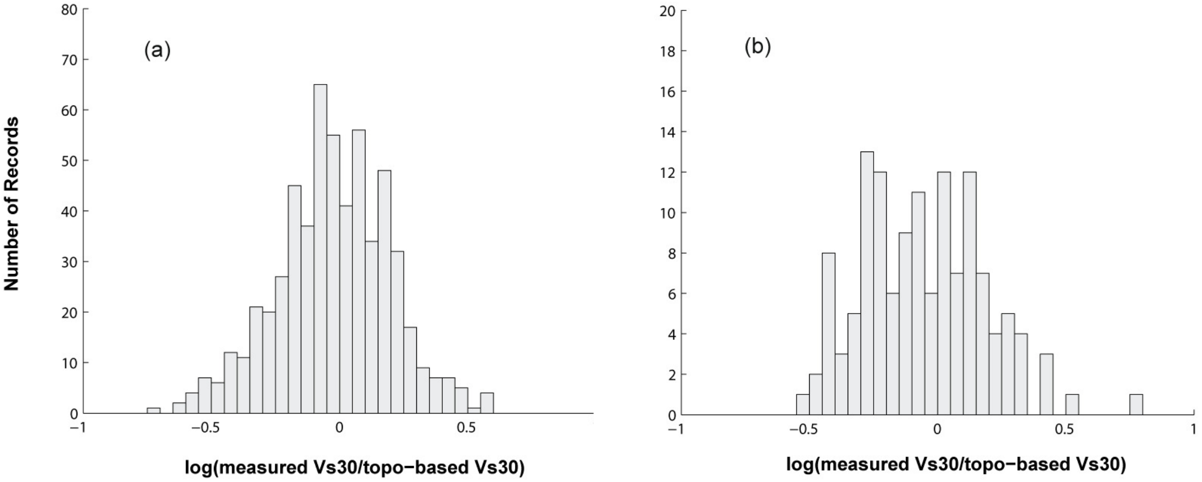


Figure 6: Histograms indicating logarithmic differences of measured $V_{s,30}$ values compared to those estimated by the approach of Wald and Allen (2007). For active regions (a) the bias is -0.024 and the standard deviation is 0.221 and for stable regions (b) the bias is -0.056 and the standard deviation is 0.241.

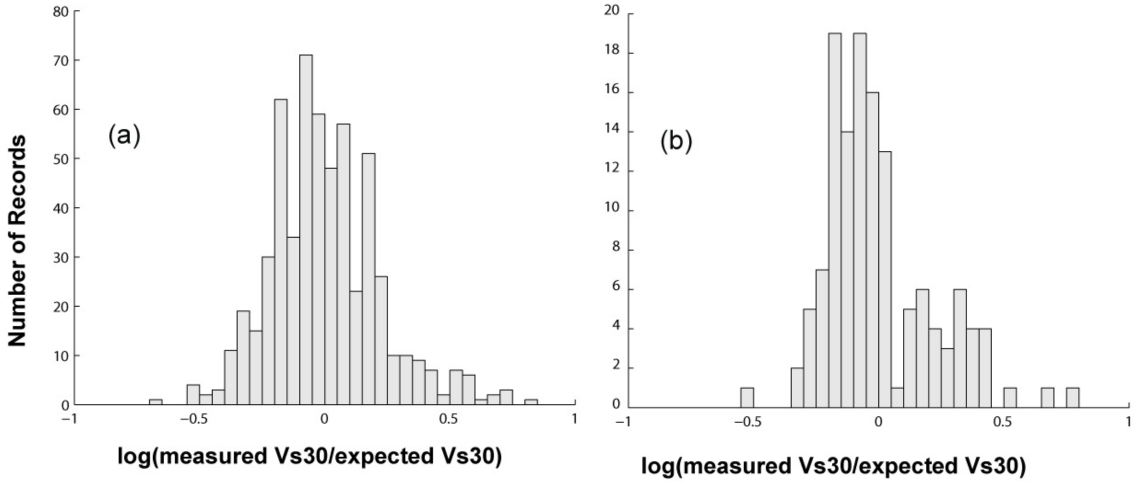


Figure 7: Histograms indicating logarithmic differences of measured $V_{s,30}$ values compared to the expected $V_{s,30}$ assuming a lognormal distribution (426m/s for active regions (a) and 424m/s for stable regions (b)). The biases are null as expected and the standard deviations are 0.219 for active and 0.214 for stable regions.

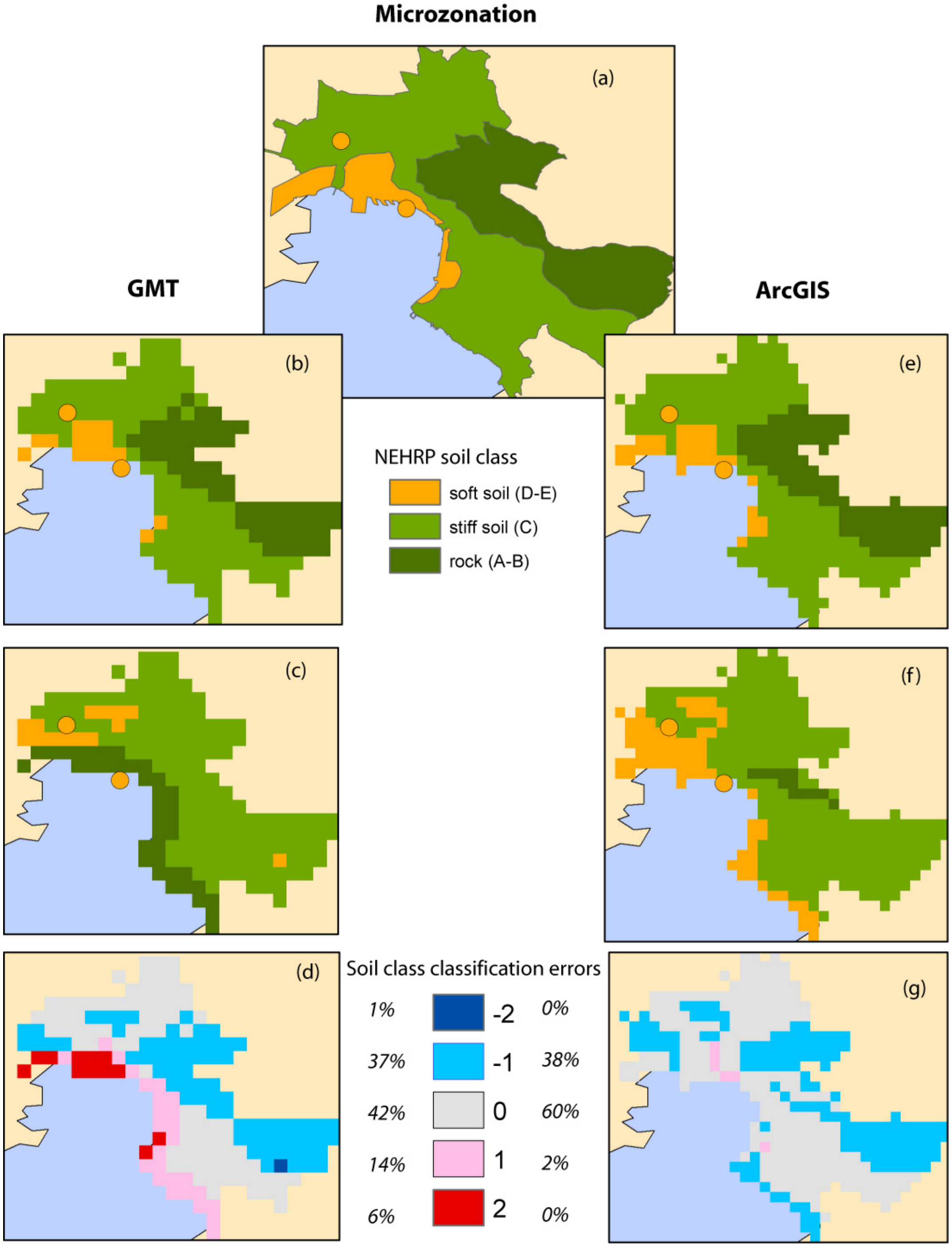


Figure 8: a) map of NEHRP site classes for Thessaloniki given by Theodulidis et al. (2006) and b) its pixelated version at the same resolution as c) : NEHRP site classes predicted for Thessaloniki using the approach of Wald and Allen (2007) and GMT's grdgradient slope calculation method, d) the difference in site class between c and b. For example, value (2) in (d) means that soil class are underestimated by 2 classes (from B to D) by $V_{s,30}$-slope method. Percentage of area falling in each class is given in the legend. Idem for e), f) and g) using ArcGIS's slope calculation method. Due to necessary projection for ArcGIS slope calculations, pixels of GMT and ArcGIS grids do not have exactly the same size.