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A SITE RESPONSE MAP OF EUROPE

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Abstract

Topographic slope and surface geology are two popular proxies for Vs30, a measure of site response. We use both these proxies to create a NEHRP category site response map of the area covered by the Seismic Hazard Harmonization in Europe (SHARE) project.

We use the topographic slope method, based on the correlation between slope and Vs30, in tectonically active southern Europe. The slopes are determined from SRTM digital elevation data at 9 arc second resolution. The SHARE Vs30 data are from sites in Italy, Greece, and Turkey. We develop the correlation by stepping through slope and Vs30 space, calculating standard deviation and bias, and choosing the best-fit slope and Vs30 bins. The final correlation has a slightly lower Vs30 for a given slope than the standard USGS correlation.

High quality Vs30 data are sparse in tectonically stable northern Europe, and Pleistocene glaciation has disturbed the sedimentation patterns that justify the slope method. Thus, we use surface geology to define the site response. Detailed digital geology maps and unit descriptions of most northern European countries are available from the OneGeology program (www.onegeology.org). We assign site response units based on the geologic descriptions. The final site response categories do not have discontinuities at country boundaries, showing the consistency of the OneGeology descriptive rubric.

Keywords: ground motion; geology; site amplification; Europe

1. Introduction

We create a site response map of Europe (Fig. 1). 'Site response' refers to the amplification of earthquake ground motions by various types of soil. The site response map shows the distribution of National Earthquake Hazard Reduction program (NEHRP) site categories. The NEHRP site categories are defined in terms of Vs30, the average S-wave velocity in the upper 30 m of the earth (Table 1) [1, 2]. Vs30 is a good predictor of site amplification [3].

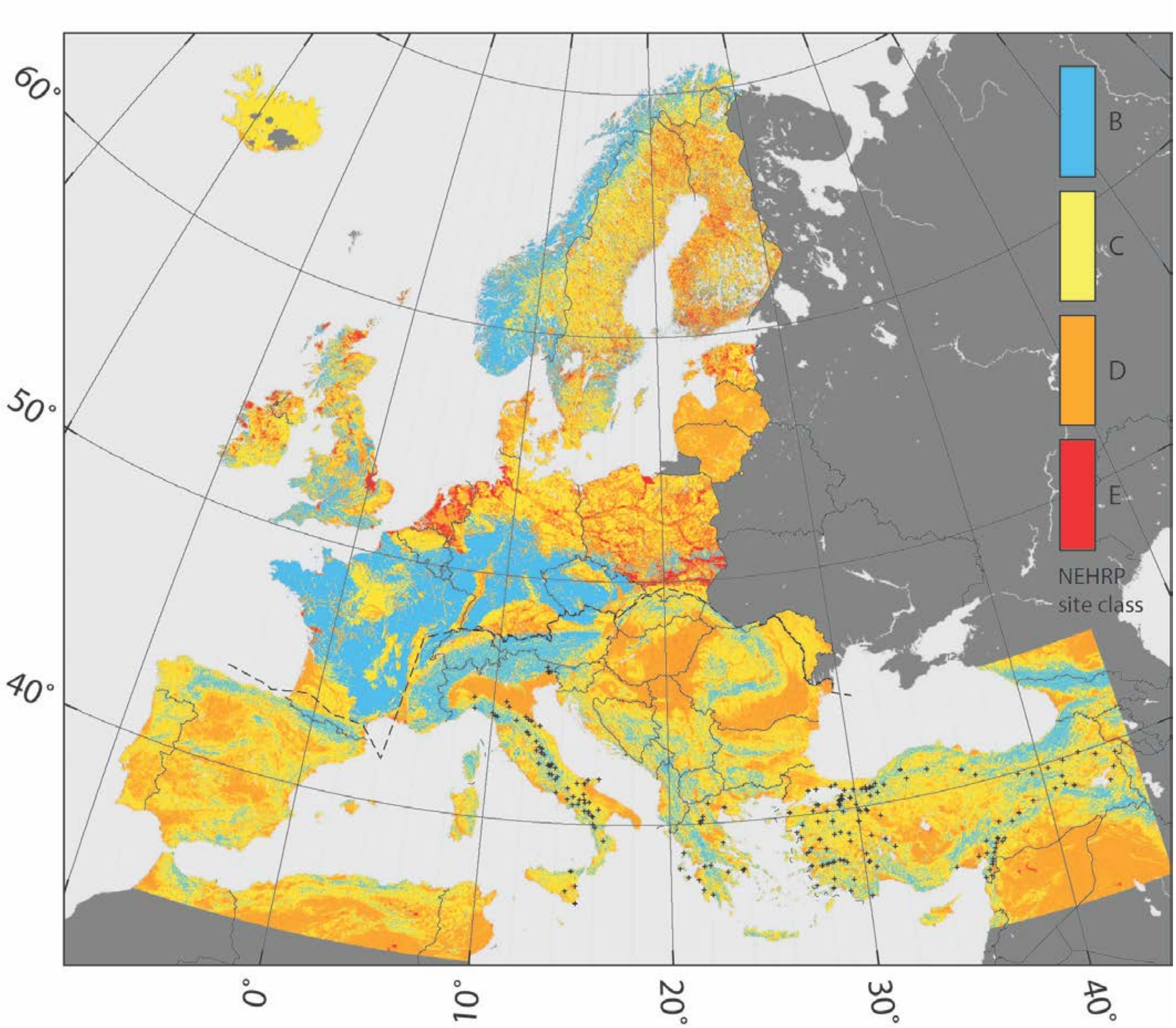

Fig. 1 – Site response map of Europe. Black crosses are locations of Vs30 measurements; black dashed line divides northern and southern Europe.

Table 1 – Site response categories defined by Vs30 [1, 2].

Site Category	Description	Vs30 Range, m/s
A	Hard rock	Vs30 > 1500
B	Soft rock	760 < Vs30 ≤ 1500
C	Very dense soil	360 < Vs30 ≤ 760
D	Stiff soil	180 ≤ Vs30 ≤ 360
E	Soft soil	Vs30 < 180
F	Soils requiring site-specific evaluations	

Here, Vs30 is not directly measured, but is determined from two types of proxies: topographic slope [4, 5], used in southern Europe; and surface geology [6, 7], used in northern Europe (Fig. 1). Reference [1] specifies that if site categories A and B are established without the use of on-site Vs30 measurements (as is the case here because we use proxies), then both categories are considered to have the same amplification – that of the reference site condition, equal to 1.0. Thus, the two categories collapse into a single category that we call B. Similarly, we lack the site-specific evaluations required for site category F, and the topographic slope proxy cannot distinguish between categories E and F, so we do not distinguish site categories E and F, and assign category E to the candidate sites. Therefore, the site response map shows the distribution of site categories B, C, D, and E.

The map is defined on a set of points covering Europe at a 0.01° latitude and longitude spacing (~1 km), herein called 'the mesh.'

Our application of the site response map is to apply site amplifications to the hazard from the Seismic Hazard Harmonization in Europe (SHARE) program as a step in producing a continental-scale earthquake risk map; therefore, the site response map is not designed for site-specific studies. SHARE is an international government-academic collaboration [8]. The hazard, and thus the site response map, provides coverage of the forty-two countries participating in SHARE. These countries are: Andorra, Austria, Belgium, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Malta, Moldova, Monaco, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, and Vatican City.

2. Topographic Slope Method

The topographic slope proxy for Vs30 was popularized by the U.S. Geological Survey (USGS) [4 ,5]. It exploits rough correlations between topographic slope and Vs30 determined from measured Vs30 values; the correlations can potentially be used where Vs30 data are lacking. The correlations exist because of the geologic processes of erosion and deposition: steep slopes are maintained by strong materials (high Vs30); over time erosion removes material from steep slopes and deposits coarse-grained sediments on medium slopes (moderate Vs30), and fine-grained material on low slopes (low Vs30) [4]. The topographic slope method is suitable for southern Europe because these geologic processes are occurring over a range of slopes, and there are adequate Vs30 data to calibrate a local correlation.

The topographic slope method is not suitable for northern Europe (*e.g.*, [9]). First, northern Europe has been subject to repeated continental glaciation in Pleistocene time [10]. That glaciation has re-set the processes of erosion and deposition, erasing any topographic slope-Vs30 correlation. Second, there are few high quality Vs30 data available in northern Europe to calibrate any potential local correlation [11]. Third, the USGS showed [4] that tectonically active (such as southern Europe) and inactive (such as northern Europe) regions require different topographic slope-Vs30 correlations. This means the southern Europe correlation determined here is not applicable to northern Europe. Further, the USGS inactive correlation (based on Australian and eastern U.S. data) is not applicable to northern Europe because of its glacial history. Therefore, the northern Europe site response categories are determined from surface geology.

2.1 Data

The Vs30 data come from a predecessor to the SHARE program [12]; essentially the same data are reported by SHARE [11]. The data in [11, 12] include Vs30 values at about 400 locations that were measured by various methods and inferred by various proxies; we filtered those data so that we use only the 148 measured Vs30 values. The slope at the Vs30 sites in southern Europe is computed from SRTM 9 arc-second (~280 m) elevation data [13]. The final Vs30 data come from three countries: Greece, Italy, and Turkey. Inspection of Fig. 2 shows there are no systematic differences between the slope-Vs30 characteristics in the three countries.

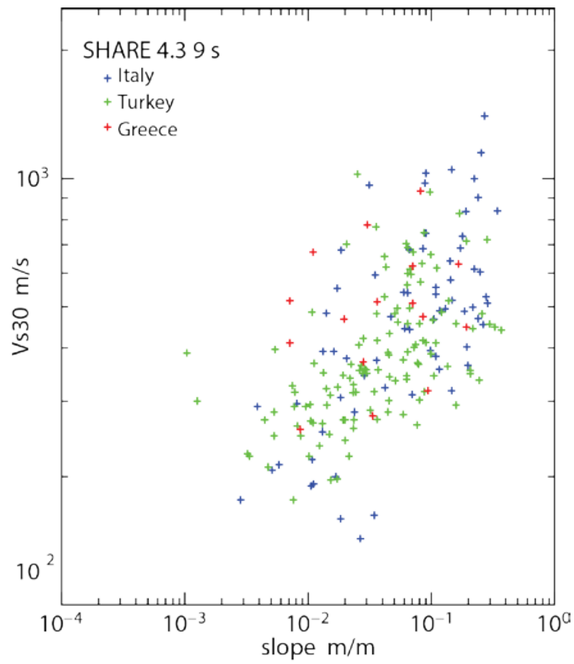

Fig. 2 - The topographic slope-Vs30 data by country; Italy (blue crosses), Turkey (green crosses), and Greece (red crosses). The data from all countries occupy the same slope-Vs30 space.

2.2 Model

In southern Europe we step through slope and Vs30 bins to develop a piecewise continuous Vs30-slope correlation. We select the best model (Fig. 3 and Table 2) based on three criteria: (i) bias and standard deviation are among the smallest; (ii) the correlation will not have greatly different slopes in neighboring bins with adequate data; and (iii) the Vs30 bin boundaries can be matched to NEHRP categories (Table 1). Because there are no Vs30 data at very low slopes (less than ~10^{-3}), the location of the inflection point at the category E/D boundary (at slope $5x10^{-4}$) is selected to minimize residuals of the lower Vs30 range of the category D correlation. Likewise, there are no Vs30 data at high slopes (greater than ~0.4), so the location of the inflection point at the category B/C boundary (at slope 0.26) is selected to minimize residuals of the higher Vs30 range of the category C correlation.

The resulting southern Europe model is given in Fig. 3 and Table 2. The USGS global model for tectonically active regions at 9 arc-second resolution [5] is also shown in Fig. 3 for comparison. The two models took somewhat different approaches: the USGS used a world-wide compilation of Vs30 data (not shown here) from tectonically active regions to fit a global average correlation, while we use only local high-quality Vs30 data to find a local regional correlation. The use of only local data allows us to examine local geological influences on the correlations (see Section 4).

The models are not widely different; the F-value (ratio of explained variance to total variance) is about 0.33 for our model and 0.26 for the USGS model, but above a confidence level of 0.66 there is little statistical difference between the models in terms of the variance explained. We examine the model residuals (observed Vs30 minus model Vs30) of the local data: our model has a slightly smaller standard deviation than the USGS model ((ln) 0.387 vs. 0.395), and a much lower bias ((ln) 0.002 vs. -0.058). Here, bias refers to the sum of observation-minus-forecast residuals divided by the number of observations.

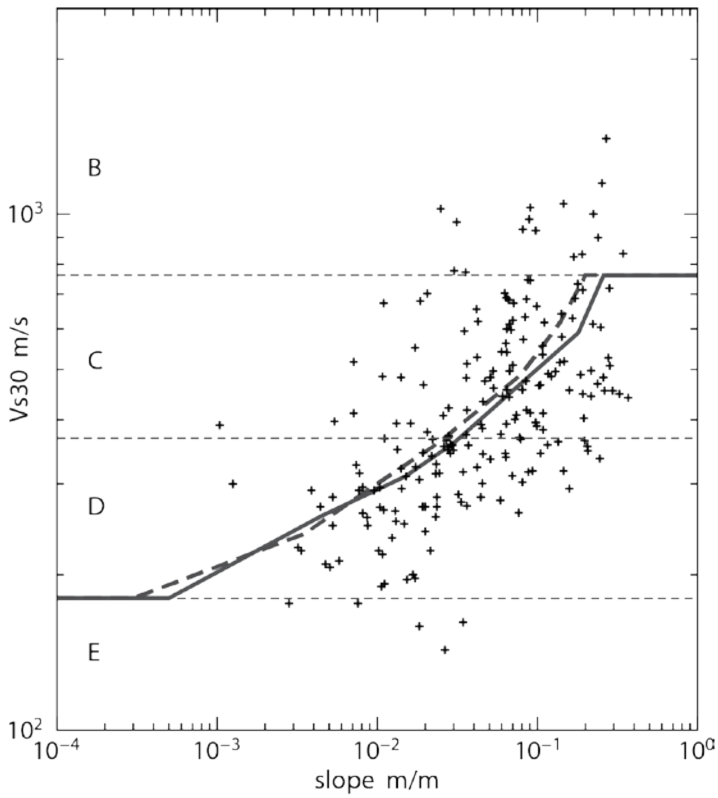

Fig. 3 - The southern Europe topographic slope-Vs30 model (thick grey line). Data are indicated by black crosses. Dashed grey line shows the USGS 9 arc-second tectonically active model [5]. Horizontal thin grey dashed lines indicate site category Vs30 ranges, as labeled.

Table 2 – Southern Europe topographic slope-Vs30 model.

Site Category	Slope, m/m		Vs30, m/s	
	Min	Max	Min	Max
E	---	0.0005	---	180
D	0.0005	0.0045	180	260
	0.0045	0.015	260	310
	0.015	0.03	310	360
C	0.03	0.18	360	590
	0.18	0.26	590	760
B	0.26	---	760	---

2.3 Results

Here we present the results of our model only. We calculate the topographic slope at each mesh point using the SRTM 9 arc-second (~280 m) elevation data. Then we determine the Vs30 values (Fig. 3, Table 2) at each mesh point, and assign a site category from the modeled Vs30 according to Table 1.

3. Geology Method

In California, the California Geological Survey (CGS) has associated many geologic units mapped in the state to typical Vs30 values, and thus site response categories [6, 7, 14]. The geologic units span a range of ages and rock and soil types, so the geology-Vs30 associations can be used elsewhere for similar geologies. We use the associations to assign site response categories to geologic units contained in digital geologic maps of northern Europe.

3.1 Data

Most of geology-Vs30 associations come from [6, 7, 14]. Glacial deposits are common in northern Europe but are not represented in the CGS work, so we use glacial deposit Vs30 values from Boston and Anchorage [15, 16]. Geologic units described as 'bogs' or 'peats' are assigned site category F by, *e.g.*, [1] and would require site specific geotechnical investigation. Here we lack those investigations, so we assign site category E to those units. Artificial fill, or reclaimed land is assigned category E because it is subject to liquefaction, settlement, and lateral spreading during earthquake motions.

We collate the associations of rock and sediment types of different ages to site categories in Table 3.

The digital geologic maps come from the 'OneGeology' program, an international effort to make maps and other geoscience data available (www.onegeology.org). The geological surveys of many European countries participate, and provide their national geologic maps in an ArcGIS format, where each geologic unit is represented by one or more shapefiles. Each country has hundreds to tens of thousands of mapped units. The OneGeology program established a unified rubric to describe the geologic units contained in the maps. The description includes a unit id, rock or sediment name, minimum and maximum age, and up to five fields of compositional information. We use the descriptions to assign site categories following Table 3.

In general, we use the geology method, based on the OneGeology digital maps, in northern Europe. Exceptions are:

- Norway and Iceland. Useable digital maps are not found on the OneGeology website, instead, we obtain digital maps that are available directly from the Geological Survey of Norway (www.ngu.no) and the Icelandic Institute of Natural History (en.ni.is) [17]. A significant portion of Iceland is covered by glacial ice; the major glaciers appear in the final map.
- Latvia and Lithuania. Latvia and Lithuania do not participate in the OneGeology program, and we can not locate any digital maps of surficial geology. Thus, we use the topographic slope method for these countries. Latvia and Lithuania are in a tectonically inactive domain. No Vs30 data are available for the two countries. We try two topographic slope-Vs30 correlations developed for inactive regions, the USGS correlation [4] and a correlation developed for the central and eastern U.S. [18]. We judge the appropriateness of each correlation by visual inspection of the continuity or contrast in the site categories at the borders of Latvia and Lithuania with neighboring countries (with site response categories based on geology). The latter correlation has the better continuity across the borders, so we use that correlation [18].
- Artificial fill. Artificial fill, sometimes called reclaimed land, is a concern because conventional construction practice tends to produce a deposit which is not densely packed (and therefore may have high ground motion amplification), and poses additional hazards due to high potential of uneven settlement and liquefaction because of high water table. For these reasons, all reclaimed land is assumed

to be site class E (soft soil). To identify artificial fill to include in the Europe site response map, we examine satellite imagery; artificial fill areas tend to have geometric shapes that contrast with the neighboring natural coastlines. We identify large areas of artificial fill in the cities of Ancona, Barcelona, Brest, Cagliari, Copenhagen, Genoa, Gibraltar, Hamburg, Helsinki, LeHavre, Livorno, Matosinhos, Portsmouth, Rotterdam, and Valencia. The areas of artificial fill are digitized from maps and satellite images.

Table 3 – Final site category assignments by rock/sediment type and age.

Rock/sediment type	Age	Site Class
Artificial fill	Holocene	E
Mud	Holocene	E
Peats, Bogs	Holocene	E
Chalk, Limestone	Any	B
Clastic Sedimentary Rocks	> Late Cretaceous	B
Clastic Sedimentary Rocks	< Late Cretaceous	C
Crystalline Plutonic Rocks	Any	B
Crystalline Metamorphic Rocks	Any	B
Glacial Deposits (except outwash)	< Pleistocene	C
Glacial Outwash	< Pleistocene	D
Mixed Mud Sand Clay	< Pleistocene	D
Alluvium	Pleistocene-Pliocene	C
Alluvium	Holocene	D
Sand	Pleistocene	D
Aeolian Deposits	< Pliocene	D
Volcanic Rocks	< Late Cretaceous	C
Volcanic Rocks	> Late Cretaceous	B

3.2 Results

Following the associations in Table 3, we assign a site response category to each shapefile. Then, we extract the site categories from the shapefiles at the mesh points. In Fig. 1, we note a desirable feature: the site category assignments are generally continuous across national borders. This demonstrates that each countries' geology descriptions from OneGeology are sufficient to reliably assign consistent site categories.

4. Comparing the Geology and Topographic Slope Methods

It is useful to compare the site categories determined by the two methods as a check on the site consistency. We compare the two methods in Italy, which participates in the OneGeology program, and where there are many Vs30 measurements used to calibrate the topographic slope correlation (Fig. 1, Fig. 2). We compare the Italian site category assignments made by the two methods on the latitude-longitude mesh.

4.1 Sediments

We determine the matches and mismatches of the site category assignments made by both methods in Italy. We find that 57% of the mesh points have the same site category, and an additional 37% have a difference of one category (*e.g.*, category B by one method and C by the other). Only 6% of the mesh points differ by more than one category (*e.g.*, category C by one method and E by the other).

A comparison of the Italy geology-based and topographic slope-based models shows that a major cause of the difference of one category is the sediment deposits of the Po Valley (in northern Italy) and the river deposits fringing most of the country. These deposits are given site category E by the geology method and mostly category D in the slope method. Examination of the Vs30 values from the sediment deposits of the Po Valley fall in the category D range and not E.

The problem is that the OneGeology sediment description was too general, with too many sedimentary processes combined. The description of the sediment unit from the Italian OneGeology file is “Deltaic, alluvial and coastal plain deposits; aeolian deposits,” a broad description that lumps together several sedimentary processes that were initially conservatively assigned a category E. The individual Vs30 values, and the topographic slope models (our model and the USGS model), show category D is more appropriate. Caution for any ambiguous or overbroad terms should be exercised when using the OneGeology descriptions.

4.2 Limestone

Limestones may not be well modeled by the topographic slope method. For example, [4] assigned topographic slope-based site categories near the D/E boundary to the flat-laying limestone Nullarbar Plain of Australia, while [19] assigned a geology-based C site category. The difference may be due to the weathering characteristics of limestone: it may dissolve chemically in addition to breaking into clastic fragments.

We examine the slope at the few locations where Vs30 is measured in limestone. The slope model would predict values of ~300 to ~760 m/s whereas the measured Vs30 values range from ~650 to ~1500 m/s. Therefore, in areas of pure limestone in southern Europe, we replace the slope-based site categories with site category B (as in Table 3), typical of the measured Vs30 values. Note this replacement can be achieved only in the southern European countries participating in the OneGeology program, from which the limestone extent can be defined.

5. Results and Conclusions

We combine the site response assignments from the topographic slope and geology methods to create an integrated site response map (Fig. 1). The join between the northern and southern Europe results is placed along various river basins separating northern and southern Europe (dashed black line in Fig. 1). The site response assignments on either side of the join are similar, so the final map does not have unwanted discontinuities. Without the guidance of the join line, it is difficult to tell the location of the join.

In conclusion, a regional site response map covering the SHARE countries is developed using a combination of the topographic slope and geology methods, and the two methods are combined in a seamless manner. We will use the site response map to apply NEHRP soil amplifications to the SHARE seismic hazard as a step in producing a Europe earthquake risk zone map.

6. Acknowledgements

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