INSTRUMENTAL SUBSOIL CLASSIFICATION OF CALIFORNIAN STRONG MOTION SITES BASED ON SINGLE-STATION MEASUREMENTS

D. H. Lang[1] and J. Schwarz[2]

ABSTRACT

One of the world's largest strong-motion networks, consisting of more than 1,200 accelerographs either installed in the free-field or inside of buildings, is contained within the borders of the state of California. Most of the stations are owned and maintained by the United States Geological Survey (USGS) and the California Strong Motion Instrumentation Program (CSMIP).

In contrast to the large amount of high-quality strong-motion data from this network, an elaborated classification of the station's subsoil conditions into groups that might share similar site amplifications is not available for most of the stations.

During a measurement campaign in spring 2004, instrumental microtremor recordings were conducted at nearly 300 strong-motion sites in the central and southern parts of California, providing the basis for a fast and cost-effective classification including even deep-sediment recording sites.

The site classification method is based on the spectral H/V-ratios of microtremor data recorded at the ground surface. These ratios represent the quasi-transfer function of the underlying soil profile, and therefore a quick site classification can be carried out by comparing the shape of H/V-ratio with the transfer function of a complying theoretical model profile or by simply arranging the H/V-peak into ranges of possible peak locations. Such a site classification scheme contains more information about the site than the commonly used average shear-wave velocity in the upper 30 m. The scheme involves the total thickness of sedimentary layers over geological bedrock in addition to the shear-wave velocities. Similar schemes have been proposed before (e.g. Bray & Rodríguez-Marek, 1997) and are incorporated in several international seismic code provisions, e.g. of Germany (DIN 4149:2005).

[1] Postdoctoral Research Assistant, Earthquake Damage Analysis Center (EDAC), Bauhaus-University Weimar, Marienstr. 7, 99421 Weimar, Germany, lang@uni-weimar.de

[2] Head of Earthquake Damage Analysis Center (EDAC), Bauhaus-University Weimar, Germany

Introduction

Within the state of California one of the world's largest strong-motion network is in operation. More than 1,200 accelerographs are installed in the free-field, at the ground level of small buildings, or at different story levels of larger structures providing a unique database of near-field earthquake recordings.

With some exceptions, the majority of the stations are owned and maintained by the United States Geological Survey (USGS) and the California Strong Motion Instrumentation Program (CSMIP).

Unfortunately, an elaborated and consistent classification of the station's subsoil conditions according to an established categorization scheme, e.g. 1997-UBC (ICBO, 1997) is not available. This is because seismic velocities and geologic logs from borehole measurements or seismic experiments are missing for most of the strong-motion sites. A compendium of available *P*- and *S*-wave velocity profiles and geologic data at a number of strong-motion sites in California is given by Boore (2003). In total, Boore (2003) summarizes the data of 277 boreholes in California, of which 160 are located in the vicinity of strong-motion stations. Since the assignment of borehole sites to strong-motion stations is solely based on the distance between them, a blind assumption of the geological subsurface properties may lead to misinterpretations of site-specific amplification potential.

In addition to this, the drilling depths of most boreholes did not reach geological bedrock. This impedes the classification of the subsoil profile not only according to the consistency of near-surface soil materials (i.e. $v_{s,30}$) but also the total sedimentary thickness H_{tot}.

In order to allow a more refined classification of subsoil conditions, even at those sites where geological information is missing, a hybrid procedure based on instrumental measurements and analytical investigations (analogy considerations) was developed.

Instrumental measurements and data analysis

During a measurement campaign from April to June 2004, instrumental recordings of ambient seismic noise (microtremors) were conducted at nearly 300 different strong-motion sites in the central and southern parts of California. Figure 1 shows the respective region of California with observed strong-motion stations. Primarily, the measurements were carried out between the south coast of San Pablo Bay in the North (north of San Francisco) and Imperial Valley in the South.

The instrumental measurements were carried out during the daytime using a RefTek data acquisition system (72A series) and a triaxial seismometer (type Lennartz LE-3D/5s). At each site microtremors were recorded with a sampling rate of 100 Hz for approximately 30 minutes with the exception of very deep-sediment sites (as e.g. in the Imperial Valley region). Here recordings lasted nearly 60 minutes. During the measurements particular attention was given to keep the recordings free from very local noise sources, like e.g. passing pedestrians, vehicles or operating machineries. Meteorological disturbances, e.g. rainfall or gusty wind, did not occur during the observation period. The site's topography and local peculiarities were also considered, e.g. artificial soil replenishments, floor coverings, paved or tarmac roads, and neighboring elevated structures.

Each component (V, H_1, H_2) of the overall recording duration was divided into several time windows each having a length of 81.92 s (8,192 samples), or 163.84 s (16,384 samples) in case of very deep-sediment sites. Then, Fast Fourier Transformation spectra (*FFT*) were calculated for each time window of the vertical and both horizontal components. After smoothing the curves of *FFT*-spectra, horizontal-to-vertical spectral ratios (*HVNR*) were generated for each time window.

The application of the spectral H/V-method (Nakamura, 1989) establishes the main basis for the herein elaborated site classification procedure. Since geotechnical or seismic exploration methods are time-consuming and costly, this single-station technique based solely on microtremor data has become more and more popular to obtain information on the site's subsoil (Lang *et al.*, 2004; Lang, 2004).

Examples of spectral H/V-ratios of microtremors recorded at different sites will be illustrated in a later section of the paper (cf. Figures 4 and 6: the bold lines represent the arithmetic mean value of spectral H/V-ratios for all successive time windows, the gray-shaded area marks the range of the 16% and 84% fractiles, respectively.)

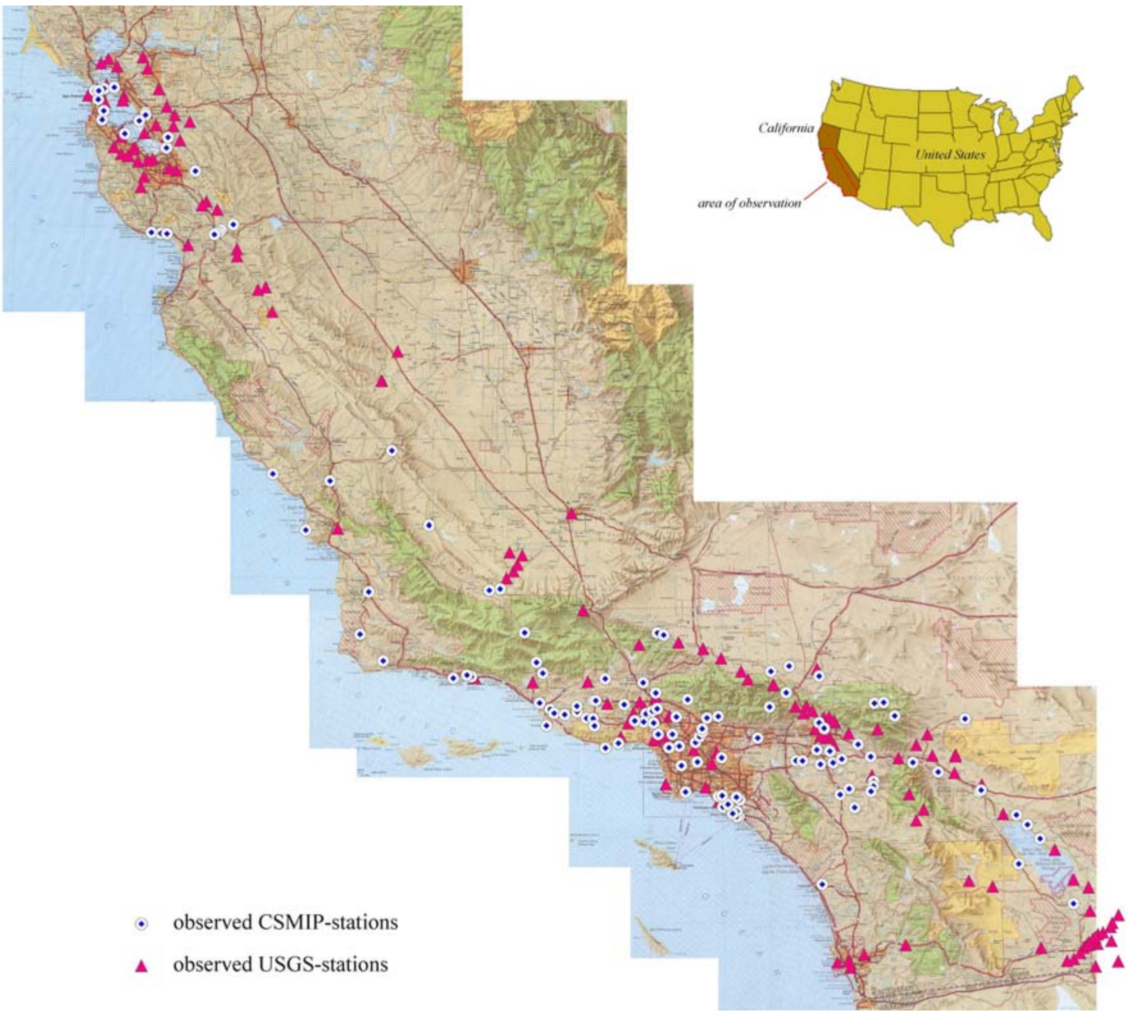


Figure 1. Map of central and southern California with instrumentally observed strong-motion sites. (Modified road map by Freytag and Berndt – *Karto*+*Grafik* Frankfurt/M.)

Site classification

The consistency of the near-surface subsoil layers has significant influence on the transfer and amplification characteristics of strong ground motion. When interpreting structural earthquake damage, local site amplification should be accounted as one of the major damage-contributing factor. Therefore, earthquake resistant design codes require the identification of local subsoil conditions and the consideration of site amplification potential to provide reliable seismic action type (cf. Figure 2). To keep matters simple, a more or less detailed classification of local subsoil conditions and a subdivision into distinct site classes must be performed.

Overview of classification schemes

A variety of classification schemes can be found in almost every international seismic code provision. In general these schemes can be subdivided into three different types: stiffness-related, stiffness-and-depth-related, and hybrid classification schemes.

Stiffness-related classification schemes are always limited to a certain range of soil depth (in general 30 m), whereas the average shear-wave velocity of the respective soil materials $v_{s,30}$ is the main criteria for classification. In addition to numerous other earthquake code provisions, the Uniform Building Code 1997-UBC (ICBO, 1997) also makes use of this classification principle by distinguishing between NEHRP site classes A – F (BSSC, 1995). Elastic design spectra for site classes B – E are displayed in Figure 2.

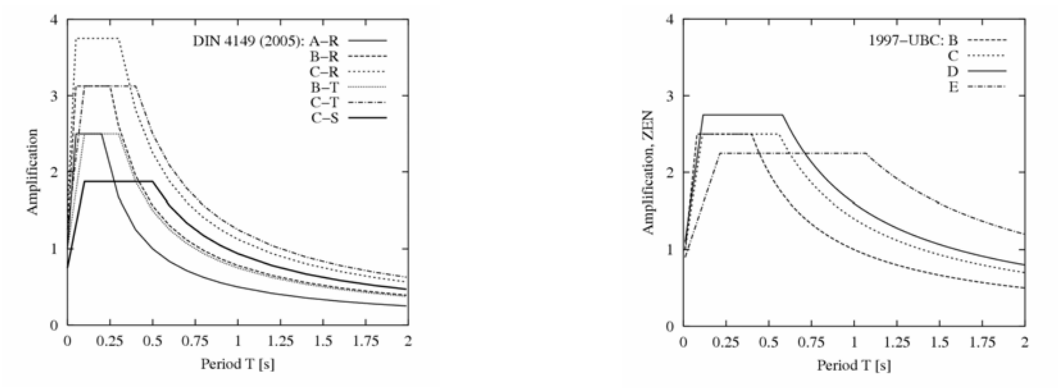
In addition to soil consistency of the uppermost soil layers, stiffness-and-depth-related classification schemes cover the depth-extension (total thickness H_{tot}) of sedimentary soil layers. This principle of site classification is contained in the current earthquake code of Germany DIN 4149:2005 and differentiates between the consistency of soil materials of the uppermost 25 m and the total thickness of sedimentary soil layers above geological bedrock (Schwarz *et al.,* 1999). Thus a more precise description of seismic action and design loads can be realized. Table 1 illustrates the possible combinations of soil condition classes A, B, C, and geological subsoil classes R, T, S. Their corresponding elastic design spectra as specified in the German code DIN 4149:2005 are given in Figure 2.

Table 1. Possible combinations of site-specific subsoil classes of the German earthquake code DIN 4149:2005.

Geological subsoil class: / Soil condition class:		**R**: areas pred. characterized by rocks	**T**: transition zones between R and S	**S**: sediment basins
		H_{tot} < 25 m	H_{tot} < 100 m	H_{tot} > 100 m
A: firm to medium-firm soil	$v_{s,25}^{*} > 800$ m/s	A-R	-	-
B: loose soil (gravel to coarse sands, marls)	$350 < v_{s,25}^{*} < 800$	B-R	B-T	(B-S)**
C: fine-grained soil (fine sands, loesses)	$150 < v_{s,25}^{*} < 350$	C-R	C-T	C-S

* Average shear-wave velocity of the uppermost 25 m of subsoil materials [*m/s*].

** As proposed by Lang *et al.* (2004). Combination B-S is not considered in DIN 4149:2005.



(a) DIN 4149:2005 *(b) 1997-UBC (ICBO, 1997)*

Figure 2. Elastic response spectra (damping ξ = 5%) for site classes of the earthquake code provisions *(a)* DIN 4149:2005 and *(b)* 1997-UBC (ICBO, 1997).

A reliable site assessment on the basis of the aforementioned "conventional" classification procedures can only be performed if sufficient information on the local subsoil conditions is available. For this reason, hybrid site categorization methods have been developed that consider the predominant site frequency f_s as an additional differentiating factor. Since site response estimation techniques (e.g. spectral H/V-method) are suitable for deriving the quasi-transfer function of the recording site's subsoil and thus its fundamental site frequency f_s, an alternative site classification can be achieved even when geotechnical information on the subsoil is missing. An innovative example of a hybrid site classification scheme was presented by Bray and Rodríguez-Marek (1997). The proposed classification follows the 1997-UBC scheme (ICBO, 1997) and is summarized in Table 2, primarily subdividing the NEHRP site classes (BSSC, 1995) according to the thickness ranges of sedimentary soil layers H. Although the indicated ranges for fundamental site frequencies f_s seem to be determined by using the results of theoretical calculations for possible combinations of average shear-wave velocities v_s and total sediment thickness H_{tot}, a site classification based on instrumental data could be carried out.

Development of an innovative hybrid classification scheme

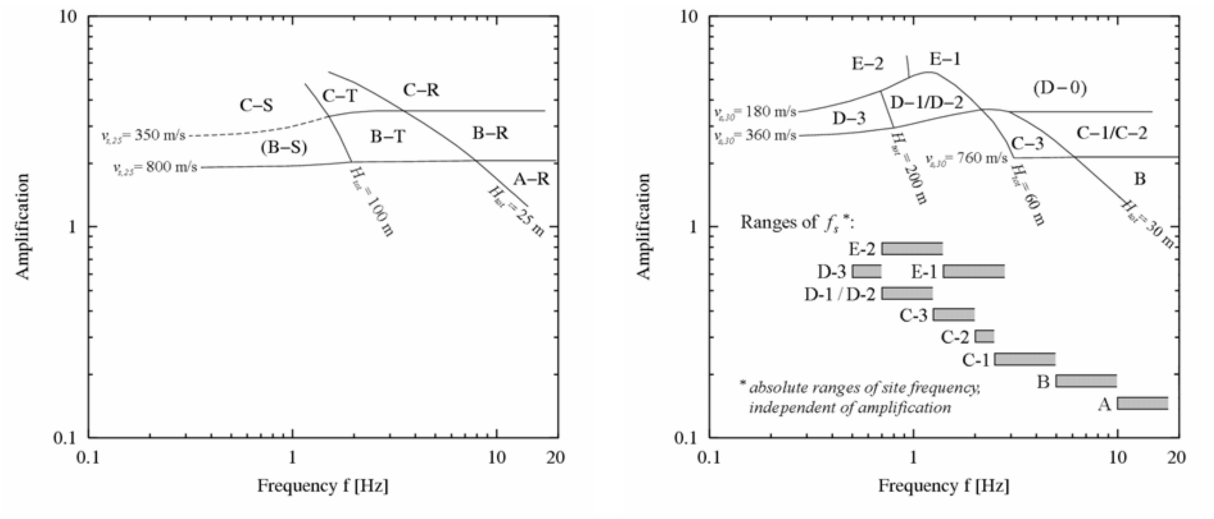
In order to allow a reliable, fast and easy site classification even with no or only coarse information on the site's subsoil, a classification procedure based on instrumental data was developed. Due to standardization reasons, the classification avails oneself of the site classes of the German earthquake code DIN 4149:2005 and the subdivided NEHRP site classes according to Bray and Rodríguez-Marek (1997). Since the site classes of both classification schemes can be described by a range of average shear-wave velocity in the uppermost soil materials ($v_{s,25}$ resp. $v_{s,30}$) and by a range of total sedimentary thickness H_{tot}, a variety of one-dimensional subsoil profiles can be modeled that meet the upper and lower boundary conditions of the respective site class.

Table 2. Sub-categorization of NEHRP site classes (BSSC, 1995) according to ranges of sedimentary layer thickness as proposed by Bray and Rodríguez-Marek (1997).

NEHRP site class	Site class *	Description	Ranges of shear-wave velocity $v_{s,30}$	Comments on layer thickness H	f_s [Hz] **
A	A	Hard, strong, intact rock	$v_{s,30} > 1500$ m/s	–	≥ 10
B	B	Rock (most California rock cases)	$v_{s,30} \geq 760$ m/s or	$H < 6$ m of soil	≥ 5.0
C	C-1	Weathered/soft rock	$v_{s,30} \geq 360$ m/s	$H = 6 – 30$ m	≥ 2.5
	C-2	Shallow stiff soil		$H = 6 – 30$ m	≥ 2.0
	C-3	Intermediate depth stiff soil		$H = 30 – 60$ m	≥ 1.25
D	D-1	Deep stiff Holocene soil, either sand or clay	$v_{s,30} \geq 180$ m/s	$H = 60 – 200$ m	≥ 0.7
	D-2	Deep stiff Pleistocene soil, either sand or clay		$H = 60 – 200$ m	≥ 0.7
	D-3	Very deep stiff soil		$H > 200$ m	≥ 0.5
E	E-1	Medium depth soft clay	$v_{s,30} < 180$ m/s	Soft clay layer: $H = 3 – 12$ m	≥ 1.4
	E-2	Deep soft clay layer		$H > 12$ m	≥ 0.7
F	F	Special, e.g. potentially liquefiable sand or peat	*not specified*	*not specified*	≈ 1.0

* Refined NEHRP site classes according to Bray and Rodríguez-Marek (1997).

** Predominant frequency of the subsoil profile (site frequency). Absolute (amplitude-independent) ranges of f_s are drawn into the sketch of Figure 3b.



(a) DIN 4149:2005 *(b) Bray & Rodríguez-Marek (1997)*

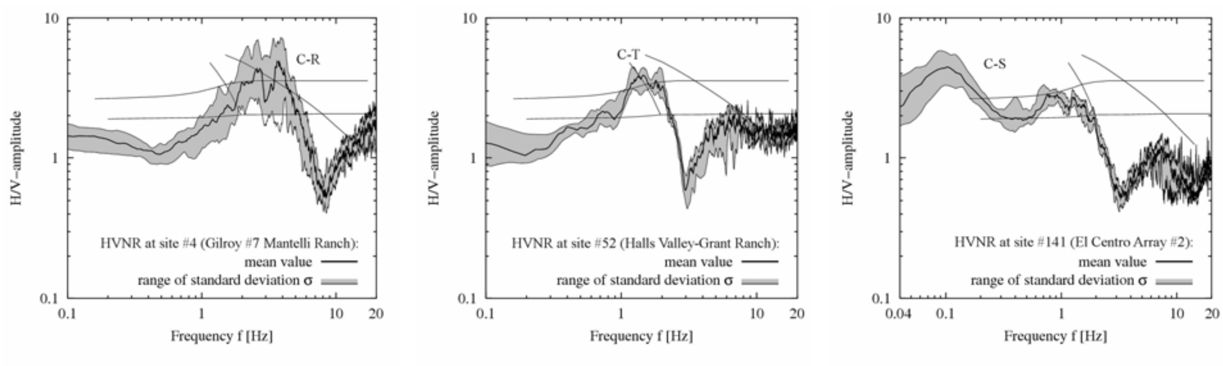
Figure 3. Qualitative ranges of possible peak locations of one-dimensional transfer functions for *(a)* site-specific subsoil classes according to DIN 4149:2005 and *(b)* refined NEHRP site classes by Bray & Rodríguez-Marek (1997).

In the next step, one-dimensional transfer functions can be calculated for each model profile. Because the location of the predominant frequency peak of the theoretical transfer functions can be regarded as a function of average soil consistency and total sedimentary thickness, a qualitative range of possible peak locations in the frequency-amplification domain can be evaluated for each site class. Figure 3 depicts the ranges of possible peak locations for generated site classes based on the criteria of DIN 4149:2005 and Bray and Rodríguez-Marek (1997).

By arranging the quasi-transfer function TF_{quasi} of instrumentally obtained data (here spectral H/V-ratio on microtremors) into the possible ranges of predominant peak locations, the classification of the recording site into site classes of DIN 4149:2005 or refined NEHRP site classes by Bray and Rodríguez-Marek (1997) can be determined. In both schemes, horizontal borderlines separating the different site classes represent the level of soil consistency, i.e. shear-wave velocity $v_{s,25}$ resp. $v_{s,30}$. The higher the level of amplification, the softer the soil consistency is (the smaller the average shear-wave velocity). In addition, diagonal proceeding borderlines are a measure of total sedimentary thickness H_{tot}. With decreasing frequency f, soil thickness H_{tot} increases.

An assimilation and check of reliability of both classification schemes was performed on the basis of those investigated strong-motion sites in California where detailed information on seismic velocities and subsurface stratigraphy are disposable. A classification scheme representing an earlier state of elaboration was successfully applied to recording sites in Turkey (Lang *et al.*, 2004) and Germany (Lang, 2004). Figure 4 exemplarily illustrates the classification of 3 recording sites into the site classes of DIN 4149:2005. Even though each of the three sites already were classified as soft soil sites according to conventional procedures ($v_{s,30}$ < 360 m/s), a more refined classification can be achieved by considering the range of sedimentary soil thickness H_{tot}.

Once the site is classified using one of these methods, a calibration of an appending model-profile can be achieved. By variations of the average soil stiffness and/or the sedimentary soil thicknesses, an approximation of the theoretical transfer function TF_{theo} to the experimentally obtained transfer function TF_{quasi} (i.e. the spectral H/V-ratio on microtremors) can be performed. Reliability of results increases with any available subsoil information. A validation of this calibration procedure was conducted at borehole sites in San José, California (Lang and Schwarz, 2005).



(a) 1595: Gilroy #7 Mantelli Ranch *(b) 1422: Halls Valley – Grant Ranch* *(c) 5115: El Centro Array #2*

Figure 4. Spectral H/V-ratios of microtremors overlain with the classification scheme based on DIN 4149:2005 site classes.

Application to strong-motion sites in California

Instrumental recordings were conducted at 287 strong-motion sites in the central and southern part of California. Geologic boreholes are sited in the vicinity of 73 strong-motion stations, but both sites do not always share similar subsurface velocity properties. The information on the seismic velocities and stratigraphy of the geologic logs are published in numerous USGS Open-File Reports (http://infotrek.er.usgs.gov/pubs/). More information on subsurface properties of Californian strong-motion stations were found in Graves and Wald (2004), Joyner and Boore (1981), Stewart and Baturay (2001).

To illustrate the procedure's reliability, results of 3 recording sites on the eastern shore of San Francisco Bay, California, are compared with a recently published map of NEHRP $v_{s,30}$ site classes based on cone penetration test (SCPT) soundings, soil thicknesses, and shear-wave velocities of shallow geologic units (Holzer *et al.,* 2005). According to Figure 5, geological subsoil conditions at each of the three sites can be allocated to NEHRP site class D (180 m/s ≤ $v_{s,30}$ < 360 m/s), whereas adjacent areas are characterized as site class E ($v_{s,30}$ < 180 m/s). Figure 6 shows the spectral H/V-ratios of microtremors (*HVNR*) recorded at the three sites sorted into the classification scheme for refined NEHRP site classes. The locations of the predominant peaks in the spectral range yields a classification of the sites between site class D-3 and E-2. This in turn points to an average shear-wave velocity $v_{s,30} \approx 180$ m/s and a total sedimentary thickness above bedrock H_{tot} < 200 m (58472: Oakland O.H.W.), ~ 250 m (1756: Alameda F.S. #4), and ~ 300 m (1755: Alameda F.S. #1). A verification of these results can be determined using the strong-motion station 58472, as borehole measurements have been conducted in the vicinity of this site. In Gibbs *et al.* (1992) measurements at borehole #122 reaching down to a depth of 155 m (but not reaching geological bedrock) are described, revealing a shear-wave velocity $v_{s,30}$ = 249 m/s.

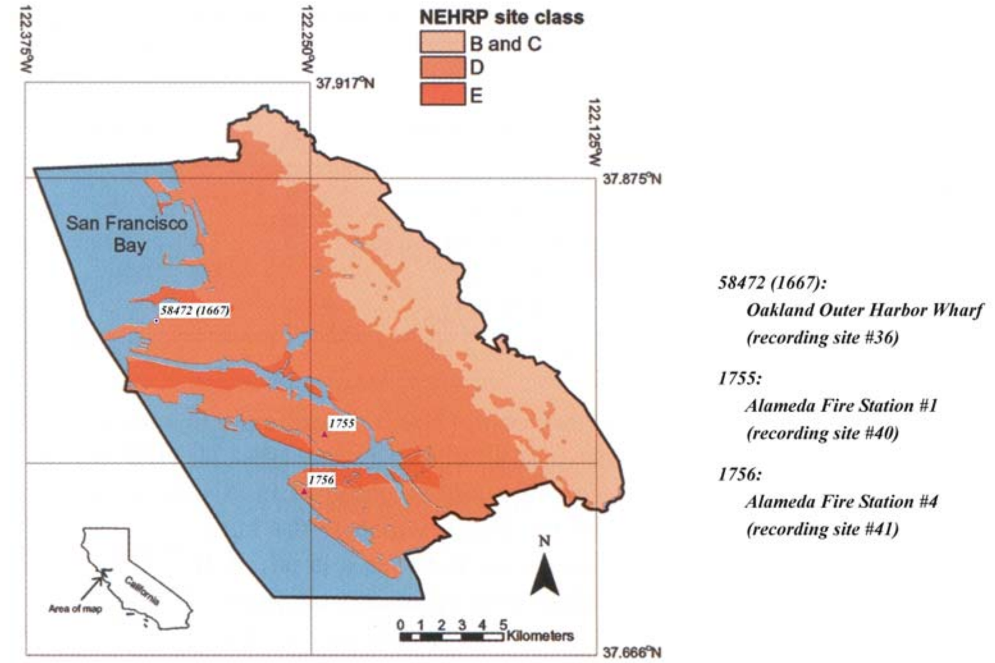
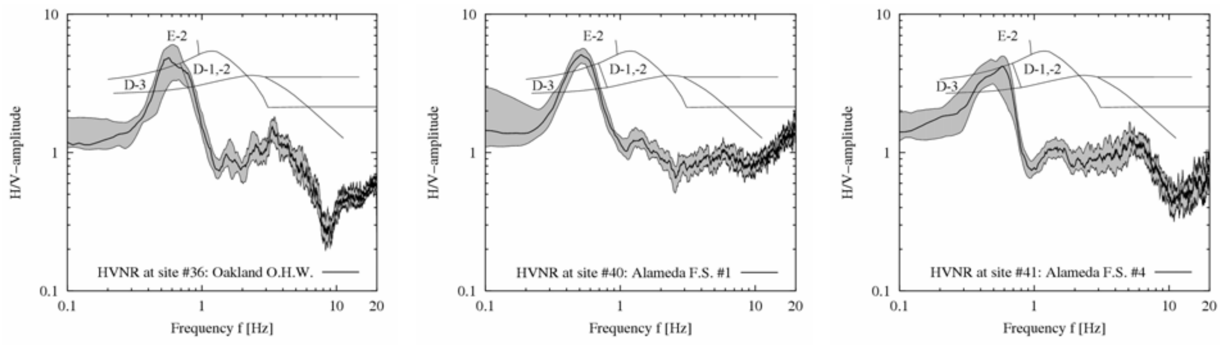


Figure 5. Map of NEHRP $v_{s,30}$ site classes by Holzer *et al.* (2005) on the eastern shore of San Francisco Bay with sites of instrumentally observed strong-motion stations.



(a) 58472: Oakland Outer Harbor Wharf *(b) 1755: Alameda F.S. #1* *(c) 1756: Alameda F.S. #4*

Figure 6. Spectral H/V-ratios of microtremors recorded at the strong-motion stations shown in Figure 5 overlain with the derived classification scheme for refined NEHRP site classes following Bray and Rodríguez-Marek (1997).

Summary and outlook

Based on single-station seismic measurements at the ground surface a procedure was developed to obtain a fast and easy classification of the recording site. To allow a widespread application and to ensure comparability with other results, the procedure relies on site classes of two popular earthquake resistant design codes DIN 4149:2005 and 1997-UBC.

With respect to the large amount of strong-motion stations in California with missing subsurface information or being only coarsely classified, the herein presented procedure and its application at 287 sites in Central and Southern California may contributes to increased knowledge of the subsurface conditions at these recording sites.

Using this procedure an estimation of the total sedimentary thickness even at deep-sediment sites where boreholes usually do not reach geological bedrock can be carried out.

Based on the hybrid site classification, a more refined calibration of an appending model-profile can be performed by approximating the respective theoretical transfer function TF_{theo} to the experimentally obtained quasi-transfer function TF_{quasi}, i.e. spectral H/V-ratio of microtremor data recorded at the ground surface.

As a whole, a more precise description of seismic action types can be obtained through the application of the refined site classification.

Ongoing research activities are focused on the development of more differentiated attenuation relationships considering not only the shear-wave velocity of near-surface soil layers $v_{s,30}$ (as a measure of soil stiffness) but also geological aspects in terms of total sedimentary thickness H_{tot} (Schwarz *et al.,* 2004).

Acknowledgments

We thank David M. Boore (USGS) for his personal support and providing us with seismic velocity data of Californian boreholes (cf. http://quake.wr.usgs.gov/~boore/data_online.htm).

Thanks also to Lars Abrahamczyk (EDAC) being a great help during the measurement campaign in 2004, Clemens Ende (EDAC) for analyzing instrumental data, and Lisa Holliday (University of Oklahoma) for reading through the paper and for numerous useful comments.

References

Boore, D.M., 2003. A compendium of *P*- and *S*-wave velocities from surface-to-borehole logging: Summary and reanalysis of previously published data and analysis of unpublished data, *U.S. Geological Survey Open-File Report 03-191*, U.S. Department of the Interior, 2003, 13 pp.

Bray, J. D., and A. Rodríguez-Marek, 1997. Geotechnical site categories, *Proceedings of the First PEER-PG&E Workshop on Seismic Reliability of Utility Lifelines*, San Francisco/California, 1997.

Building Seismic Safety Council (BSSC), 1995. 1994 Edition. NEHRP recommended provisions for seismic regulations for new buildings, FEMA 222A/223A, Vol. 1 (Provisions) and Vol. 2 (Commentary), developed for the Federal Emergency Management Agency, Washington, D.C.

DIN 4149:2005. Buildings in German earthquake regions – Design loads, analysis, and structural design of buildings. Normenausschuss Bauwesen (NABau) im Deutschen Institut für Normung e.V. (DIN), April 2005, 84 pp.

Gibbs, J.F., T.E. Fumal, D.M. Boore, and W.B. Joyner, 1992. Seismic velocities and geologic logs from borehole measurements at seven strong-motion stations that recorded the Loma Prieta earthquake, *U.S. Geological Survey Open-File Report 92–287*, U.S. Department of the Interior Menlo Park/California, 1992.

Graves, R.W., and D.J. Wald, 2004. Observed and simulated ground motions in the San Bernardino basin region for the Hector Mine, California, earthquake, *Bulletin of the Seismological Society of America* **94** (1), 131–146, February 2004.

Holzer, T.L., A.C. Padovani, M.J. Bennett, T.E. Noce, and J.C. Tinsley, III, 2005. Mapping NEHRP V_{S30} Site Classes, *Earthquake Spectra* **21** (2), 353–370, May 2005.

International Conference of Building Officials (ICBO), 1997. 1997 Uniform Building Code (1997-UBC), Whittier/CA, United States of America, 1997, 492 pp.

Joyner, W.B., and D.M. Boore, 1981. Peak acceleration and velocity from strong-motion records, *Bulletin of the Seismological Society of America* **71** (6), 2011–2038, December 1981.

Lang, D.H., 2004. Damage potential of seismic ground motion considering local site effects, *Scientific technical reports* **1** (ISBN 3-86068-227-X). Earthquake Damage Analysis Center, Bauhaus-University Weimar, 2004, 293 pp.

Lang, D.H., J. Schwarz, and C. Ende, 2004. Subsoil classification of strong-motion recording sites in Turkish earthquake regions, *Schriftenreihe der Bauhaus-Universität Weimar* **116**, 79–89, 2004.

Lang, D.H., and J. Schwarz, 2005. Identification of the subsoil profile characteristics at the Coyote Creek Outdoor Classroom (CCOC), San José, from microtremor measurements, In: Asten, M.W. & Boore, D.M., eds., Blind comparisons of shear-wave velocities at closely spaced sites in San José, California, *U.S. Geological Survey Open-File Report 2005–1169*.

Nakamura, Y., 1989. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, *QR of RTRI* **30** (1), February 1989.

Schwarz, J., C. Ende, and J. Habenberger, 2004. Attenuation relations for soft soil sites with regard to the depth of the underlying sediments, *Proc.* 29th General Assembly of the ESC, Potsdam 2004.

Schwarz, J., D.H. Lang, and Ch. Golbs, 1999. Elaboration of design spectra for the redrafting of DIN 4149, *Technical report,* Bauhaus-University Weimar, Institute of Structural Engineering, 1999.

Stewart, J.P., and Baturay, M.B., 2002. Uncertainty and bias in ground motion estimates from ground response analyses, *PEER Report 2002/??,* University of California, Berkeley, September 2002.