Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 758

THE IMPORTANCE OF GROUND-TRUTHING FOR EARTHQUAKE SITE RESPONSE

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ABSTRACT

One of the primary goals of earthquake research is to better estimate ground shaking during future earthquakes. To that end, earthquake site response studies are becoming increasingly popular around the world. In many cases, detailed "seismic microzonation" maps are being generated based strictly on measurements of the average shear-wave velocity of the upper 30 m (Vs30). In this article, we document the importance of ground-truthing such maps by summarising some lessons learned from large earthquakes and recent earthquake site response studies that utilise earthquake recordings from dense seismic networks (e.g., Japan, California, Taiwan) and ambient noise measurements. Large earthquakes around the world remind us that while soft soils generally amplify shaking, it is not a straightforward problem. Since the mid-1990's there has been a dramatic increase in the number of seismographs deployed in urban areas. These networks are providing critical new information on site response, including effects associated with the near-surface, basin-edge, topography and nonlinear behaviour. It is becoming clear from recent studies (e.g., Japan, Taiwan, Italy, California) that estimating earthquake site response requires more than just Vs30. A number of alternative schemes have recently been proposed, including several that incorporate both the average shear-wave velocity of the upper 10 m (Vs10) of soil and the fundamental period of the soil column based on ambient noise measurements or earthquake recordings. To understand ground shaking, one must incorporate ground shaking recordings with geotechnical and geological data. With new low-cost instruments, and the ease of data transmission and storage, recording ground shaking is now easier and less expensive than ever before. This in turn will allow for detailed seismic microzonation maps that will help to reduce losses (on both soil and rock) during future earthquakes.

Introduction

One of the primary goals of earthquake hazard assessment is to understand how the ground will shake during future earthquakes. This information can then be utilised for design purposes (typically through codes and standards), decision-making, and urban planning. A key challenge that we face is reconciling the fact that ground shaking is extremely complicated, yet building codes, designers, planners, and decision-makers require relatively simple information

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and guidelines. Ground shaking is controlled by many factors, including the earthquake source, path effects (wave propagation), and local site effects. In many countries, Vs30 (average shear-wave velocity of the uppermost 30 m) provisions have recently been incorporated into building codes. This, in turn, has led to an increasing number of detailed Vs30 maps (sometimes mistakenly called “seismic microzonation maps”) especially in urban areas. While the uppermost soil layers play an important role in site response, it is important to note that Vs30 represents only one contribution to ground shaking. It is worth remembering that the strongest shaking recorded during the Northridge earthquake was not on the soft soils of the Los Angeles basin, but rather on a small bedrock hill. The strongest shaking recorded during the Nisqually, WA earthquake was not on soft sediments directly above the earthquake, but rather on dense till 58 km from the epicentre. During the Kobe, Japan earthquake the strongest shaking occurred in a narrow belt of soils in the “moderate-to-stiff” category that extend along the edge of the basin. In a recent evaluation of the strongest ground shaking ever recorded globally (PGA > 1g and PGV > 100 cm/s), Strasser and Bommer (2009) concluded that “*although strong site effects are sometimes linked to large-amplitude ground motions, the vast majority of large-amplitude ground motions observed so far seem to be related to source and path processes*”.

While Vs30 provisions represent an improvement over previous soil provisions in building codes, it is important to know that in many cases, “other factors” will dominate site response and ground shaking. These other factors include basin effects, resonance, attenuation, and topographic effects (see discussion by Benjumea et al. 2008). Since Vs30 provisions were developed in the late 1980’s and early 1990’s, the amount of seismic data, especially on soil sites and in urban areas, has increased drastically. The purpose of this article is to summarise recent advances in seismic monitoring and highlight the critical role of ground-truthing for earthquake site response and hazard mitigation.

Vs_{30}, Building Codes, and “Microzonation”

Beginning in the mid-1990’s, Vs30 information has been incorporated into many building codes around the world. For example, in the United States - UBC (1997); Europe - Eurocode 8 (1998); Canada - National Building Code of Canada (NBCC 2005). In most cases, the code provisions are based on, or adapted from, the National Earthquake Hazard Reduction Program (NEHRP 1994) soil classification scheme (BSSC 2003). Incorporation of the NEHRP-style soil classification scheme was a relatively simple and generalized way to improve upon previous soil provisions in most building codes. The NEHRP-style code provisions (see Martin and Dobry 1994) provides for amplification factors based primarily on Vs30. In the Canadian Code, if Vs30 information is not available, site response can be estimated using the average standard penetration resistance (N_{60}) or the average undrained shear strength (Su). Amplification factors for weak shaking levels (0.1g) at short-periods (acceleration) range from 0.8 for hard rock (Vs > 1500 m/s) to 2.5 for soft soils (Vs30 < 180 m/s). These amplification factors vary with input shaking level – for example, for input shaking of 0.4g, the amplification factors at short-periods range from 0.8 (hard rock) to 1.1. It should be noted that these amplification factors are based on limited data, mainly from California, and there is considerable uncertainty associated with these factors (Finn and Wightman, 2003).

The inclusion of Vs30 information in building codes has led to an increasing number of detailed Vs30 maps being produced for urban areas – from California to New York, from Bangalore to Instanbul. Ironically, these maps, although detailed, are not detailed enough for building code (design) purposes. Site-specific studies will always be necessary for engineering design, given that surface geology (and Vs30) can change over distances of a few metres.

Vs30 maps are sometimes promoted for use by planners and for risk assessment (e.g., input for the HAZUS program). However, for urban planners and risk assessment a Vs30 map does not provide a critical piece of information – fundamental site period. It is the fundamental site period that determines if soil-building resonance is an issue and whether tall buildings or small buildings are at most risk. Hence, a Vs30 map by itself should not be used for “planning” purposes. At a minimum, a corresponding fundamental site period map would also be required.

It is critically important that users of Vs30 maps clearly understand their applications and limitations. Sometimes Vs30 maps are referred to as “seismic hazard maps”. This is not only inaccurate, but also misleading, as will be documented in the following sections of this article.

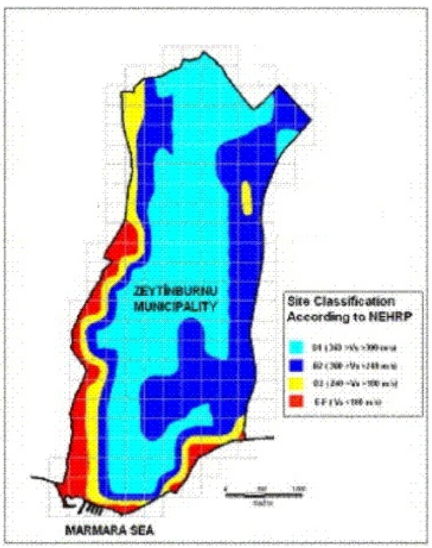

Figure 1 – Example of a NEHRP-style Vs30 soil classification map from Turkey (modified from Kilic et al. 2006).

Ground Truthing – the Critical Role of Seismic Data

Since the mid-1990’s, the number of seismic recordings, especially on soil and in urban settings, has increased dramatically (e.g., see Fig. 2). For example, after the devastating 1995 Kobe, Japan earthquake, thousands of seismometers and strong motion instruments were deployed across Japan (Aoi et al., 2009). K-NET uniformly covers all of Japan with more than 1000 strong-motion accelerometers on the free surface. In addition, KiK-net was deployed with nearly 700 strong-motion accelerometers pairs at both the surface and in boreholes at depths of 100 m or more. In Taiwan, more than 700 free-field strong motion instruments operate, in addition to dense arrays such as SMART-1, SMART-2, LSST1, and LSST2, and the Downhole Accelerometer Array in Taipei basin (DART) that consists of 10 surface and 30 borehole sensors.

In California, more than 2000 strong motion instruments are operating as of 2008. As the cost of instruments, data transmission and archiving continues to decrease, the number of instruments will continue to increase in the coming years.

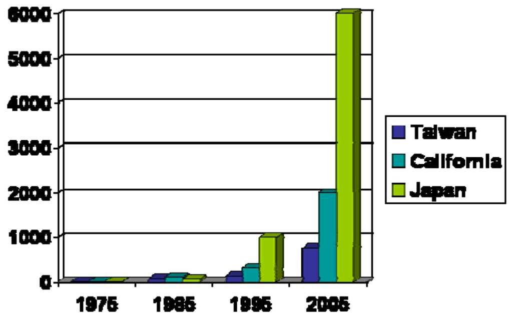

Figure 2 – The number of strong motion instruments versus time for Taiwan, California, and Japan. A similar increase in strong motion instrumentation has also occurred in Europe and Asia. Note that NEHRP amplification factors were primarily developed with pre-1990 data.

With such a large number of strong motion instruments deployed on the ground (and in boreholes) over the past decade, individual earthquakes are providing a huge quantity of strong motion data. For example, the M 7.2 Miyagi-Oki, Japan earthquake alone provided more than 2400 accelerograms (with the strongest shaking at 1.8g) from 847 stations (Strasser and Bommer, 2009). More than a dozen other earthquakes (M=6.8-8.2) in Japan that occurred between 2003 and 2009 have provided more than 1000 accelerograms (for each earthquake). These new datasets are providing critical new information on earthquake site response and the variability of ground shaking – especially on soil and in urban areas. These recent datasets are also providing new information on the role that Vs30 plays in earthquake site response. This was highlighted at the 2009 Seismological Society of America conference special session “Site Effects: Vs30 and Beyond?” (SRL, Vol. 80, No. 2). This session included 38 presentations – the majority of which described the limitations of the Vs30 method, and potential ways to move forward beyond Vs30. In the remainder of this section we highlight some “other factors” that can (and often do) play a more important role than Vs30 in controlling earthquake ground shaking at a site.

Sedimentary Basins and Basin Edge Effects

Sedimentary basins can significantly alter ground shaking through a number of mechanisms. The overall effect can be significant amplification (factors of up to ten times or more), attenuation at high frequencies, a longer duration of shaking, and a significant variation (and/or focusing) of ground shaking that is unrelated to Vs30.

A classic example of the importance of sedimentary basins is the 1995 Kobe, Japan earthquake, where a belt of concentrated damage was associated with constructive interference of S-waves with basin-induced surface waves at the edge of the basin (Kawase, 1996). Similar basin-edge effects were noted by Graves et al. (1998) in the Los Angeles Basin during the 1994 Northridge earthquake.

A number of studies have demonstrated the importance of deeper structure (from the upper 1-2 km’s to 5^+ km’s depth) in focusing energy and controlling ground shaking. Hartzell et al. (1997) examined aftershock data from the 1994 Northridge earthquake at 231 seismic stations across the San Fernando and Los Angeles Basins and surrounding mountains. The goal of their research was to evaluate the role of shallow (upper 30 m) of soil versus deeper structure (bedrock topography and basin structure to 2 km depth). They stated that "*The most important conclusion of this article is the realization that deeper structures (upper few kilometers) can play a primary role in the modification of local site response*". This conclusion has been echoed in numerous articles, including studies of various earthquakes in southern California (Field, 2000), the 2001 Nisqually earthquake near Seattle (Frankel et al. 2002), and the 2003 M 8 Tokachi-oki earthquake in Japan (Hatayama et al., 2007).

It is also important to note that thick, soft sediments can attenuate high-frequency waves, resulting in lower levels of shaking on soft soils, relative to nearby bedrock (see, for example, Figure 8.2 of Reiter 1990). On the Fraser River Delta near Vancouver BC, Cassidy and Rogers (1999) documented frequency-dependant amplification (and de-amplification). The strongest shaking they observed (Figure 3) was at the edge of the Fraser River delta, and high-frequency shaking on the thickest soils of the delta was attenuated relative to both firm soil and bedrock.

Earthquake location and rupture directivity can also play an important role in ground shaking in basins, as has been clearly shown (e.g., see Olsen et al., 2008; Molnar et al. (this volume)).

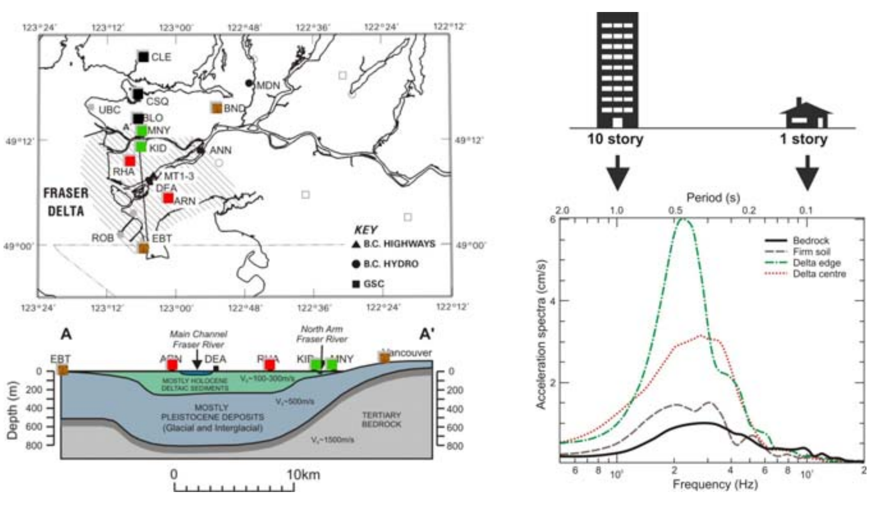

Figure 3 – Left) Fraser Delta and cross-section of delta; Right) smoothed amplitude spectra showing amplification of nearly 10 times (at some frequencies) at the edge of the delta (green) and attenuation at high frequencies on the delta-centre sites (red) relative to rock (black).

Resonance and Frequency Effects

It is important to note that the Vs30 NEHRP soil classification scheme is based primarily on data from California and resonance effects are not included. Areas of the world where very soft soil lies above very hard rock may respond differently due to large impedance contrast boundaries and strong resonance effects. Research in Italy (Gallipolli and Mucciarelli, 2009 and

Barani et al., 2008) show that for thin soils over rock, the fundamental site period may be a more useful parameter than Vs30 for characterizing site response. In Korea, Sun et al. (2005) found significant differences between observed amplifications and those predicted by NEHRP Vs30 and concluded that "*These differences can be explained by the differences in the depth to bedrock and the soil stiffness profile between Korea and western US*". In eastern Canada, where very soft clay layers overlie hard rock, clear resonance effects have been observed (see discussion in Benjumea et al., 2008). Recordings of earthquakes made in Ottawa suggest that the strong impedance contrast (resulting from soft Leda clay over bedrock) produces strong resonance effects that are not accounted for in Vs30 maps. For example, using recordings of distant, moderate earthquakes, Adams (2007) found amplification factors of up to nearly 20 times (far exceeding the Vs30 predicted amplification factors of about 2). Benjumea et al. (2008) conclude that "*Using the 30-m criterion may not provide an adequate description of the site effects in this environment*". An example is given in Figure 4, where a moderate earthquake recorded in Ottawa shows an HVSR ratio of 15 for a NEHRP "C" site (predicted amplification factor of 1.2) and about 12 for a NEHRP "E" site (predicted amplification factor of 2.5). While a NEHRP soil map might suggest that a "C" soil is safer than an "E" soil, the observations for this earthquake would suggest otherwise. Also, the fundamental site period will "determine" what size of buildings will be at greatest risk. Damage patterns attributed to soil-building resonance have been well-documented in other parts of the world (e.g., see Mucciarelli, 2009).

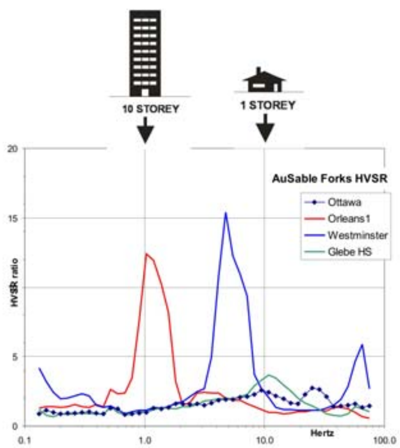

Figure 4 – OTT example – site resonance and frequency effects. Orleans (red) is a NEHRP soil classification "E", whereas Westminster (blue) is a NEHRP site class "C". NEHRP-predicted amplification factors range from 1.2-2.5. (modified from Adams, 2007).

Topographic Effects

It has long been recognized that seismic waves can be significantly altered by local topography (see Geli et al. 1988 for a summary). Amplification factors of 2-5 are often observed, and factors up to 10 or greater are sometimes observed. Numerous earthquakes have shown enhanced damage to structures at the top of hills and ridges relative to the base of the hill or nearby basins (see Ma et al. 2007, and Geli et al. 1988 for a summary). Ma et al. demonstrated that for the LA basin, topography can scatter surface waves, resulting in lower amplitude shaking (by up to 50%) within the adjacent basin. Improvements to modeling methods and larger seismic datasets ensure that understanding and prediction of site effects associated with topography will continue to improve over the coming years.

Non-Linear and Other Effects

Some thorough reviews of non-linear response of soils are presented in Kawase (2003), Boore (2004) and Choi and Stewart (2005). Modern datasets from well-recorded strong earthquakes, combined with detailed geological and geotechnical data, will provide a better understanding of non-linear effects. This in turn will lead to improvements in earthquake provisions in building codes. “Other” effects can sometimes dominate site response. One example is the damage pattern from the 2001 Nisqually earthquake, where most chimney damage corresponded with the location of the Seattle Fault zone, and is attributed to focussing of energy from shallow (<1 km) structure (Stephenson et al., 2006).

Beyond Vs_{30}

Based on the huge quantity of seismic data (collected mostly over the past decade) it is becoming very clear that earthquake site response cannot be predicted by Vs30 alone. Factors such as basin edge effects, sediment thickness, resonance, deeper structure, topography and non-linear effects have been shown to significantly contribute to local site effects. Vs30 maps do not contain information on the fundamental period of the site (e.g., Fig. 4), and this is a critical parameter (particularly for urban planners) as it links soil response with building response.

As more seismic data become available, combined with more detailed geotechnical and geological data, several alternative site classification schemes have been proposed. Most of these seek to include fundamental site period (or soil thickness) as a fundamental parameter. For example, Rodriguez-Marek et al. (2001) analyzed data from the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake and proposed a simplified geotechnical scheme that includes soil depth and thickness. Cadet et al. (2008) used data from nearly 500 stations of the KIKNET strong motion seismograph network in Japan. This network includes seismographs at the surface and at 100 m depth at each site. Their proposed two-parameter site classification includes both the fundamental period and Vs30. A detailed study in Italy by Barani et al. (2008) showed that many thin-soil sites that are classified as NEHRP-A have observed amplification factors about 50% greater than predicted. This is attributed to a strong impedance contrast between the thin soil and rock. This study concluded that for building code purposes for this type of thin-soil over rock, the fundamental site period was the most important parameter. Assimaki et al. (2008) analyzed the 2003 Miyagi-Oki, Japan aftershock sequence and concluded that “*Overall, results presented in this study highlight the need for site classification criteria to be re-evaluated and refined accordingly, opting to reflect more realistically the anticipated average response of near-surface formations.*”. Gallipoli and Mucciarelli (2009) compared amplification factors from earthquake recordings with Vs30 and concluded that “*a more reliable classification scheme should be based on a two input approach (soil Vs profile and fundamental frequency).*” The Next Generation Attenuation (NGA) model also incorporates both average shear wave velocity and soil thickness (Chiou and Youngs, 2008).

Conclusions

The topic of earthquake site response is a complex one (as summarized by Boore, 2004 and Kawase, 2003). In terms of ground shaking, it is important to remember that more often than not, earthquake source and path effects dominate the observed shaking patterns. The inclusion of Vs30 in building codes has led to the generation of detailed Vs30 maps in many urban areas around the world. However, it is important to remember that Vs30 maps do not deal with all aspects of "site response". For example, they do not provide information on fundamental frequency of the site – which is critical information for understanding whether "tall or small buildings" are most susceptible to damage. They do not deal with resonance, basin edge effects, focusing effects associated with deeper structure, or topography. Any, or all, of these "other effects" can dominate the local earthquake site response.

Since the NEHRP Vs30 provisions were developed, there has been a huge increase in the amount of ground shaking data recorded globally. These data, combined with detailed geotechnical, geological data and improved 2d and 3D modeling methods, are providing for new methods of estimating site response, that include both shallow structure, and fundamental site period. Detailed studies of basin effects (basin edge, deeper structure), resonance factors, topography, non-linear effects, and 3D modelling will all contribute to better understanding of earthquake hazards, and safer buildings and infrastructure through improved codes and standards. At this time, when Vs30 dominates site response in building codes, it is critical that we remind clients of Vs30 maps that they are not "earthquake microzonation maps", but rather only one component of microzonation (and often not the most important component).

Acknowledgments

We thank Garry Rogers for sharing his ideas (and passion) on earthquake site response, and for reviewing this manuscript. This is ESS Contribution Number 2009xxxx.

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