THE NATURE OF SITE RESPONSE DURING EARTHQUAKES

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Abstract. The traditional approach for empirical scaling of the amplitudes of strong earthquake ground motion revolves around the linear representation of the amplification of seismic waves when they propagate through soft surface sediments and soil. However, in the near field, when the amplitudes of shaking become large, the soil experiences nonlinear strains, and tensile cracks, fissures, and pounding zones form, resulting in highly nonlinear response characteristics. This means that the characteristic site response, and the patterns of amplifications measured via small earthquake records, or by analysis of microtremors, will disappear, departing from the linear amplification characteristics completely. This leads to chaos and creates a problem for seismic zoning because the nonlinear response is strongly dependent upon the amplitudes and on the time history of shaking, so that it becomes virtually impossible to predict the distribution of amplification from the local site conditions. If we assume that the observed damage distribution is a useful indication of the distribution and of the nature of shaking amplitudes, we can conduct a full-scale experiment every time a moderate or large earthquake leads to some damage. Analyses of these patterns, combined with detailed maps of the properties of the soil and of surface geology, suggest that there are reappearing patterns of nonlinear site response from one earthquake to the next. We show one such example for two earthquakes in the Los Angeles metropolitan area. This example implies that the relative movement along the boundaries of the blocks of soil, and along the cracks formed by previous strong shaking, may recur during future earthquakes. The implication is significant for all engineering analyses of response and for engineering design in the near field because it means that in the vicinity of these cracks the complexity of strong shaking is further increased by large differential motions and by large transient and permanent strains and tilts.

Keywords: effects of site response during earthquakes, local soil site conditions, local geologic site conditions, nonlinear site response, site response in near field

1. Introduction

Studies of the effects that local site conditions have on the characteristics of strong earthquake ground motion are as old as earthquake engineering. Descriptions of early investigations can be found in the papers of Reid (1910) and Sezawa, Kanai, and their co-workers (Duke, 1958). These studies first

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emerged from observations of damage, which showed considerable spatial variations and complexities. The levels of observed damage could be correlated with the available information on the site conditions, which were extracted from maps of surface soil and surface geology. Concurrent theoretical studies of linear-wave propagation, which showed amplification of amplitudes, as seismic waves emerged from "hard" into "soft" surface deposits, contributed to the formation of a view that the strong-motion shaking is amplified in the soft surface soils and sediments. This simplified view prevailed for many years, and it is evident in the formulation of early design codes (Freeman, 1932) and in the guidelines for the design of important structures (Coulter et al., 1973). A perusal of Kanai's descriptions of the patterns of damage to Japanese wooden houses, for example, reveals his appreciation for the details of many seemingly conflicting observations (Kanai, 1983), although in the end the simplifications needed for the development of design codes prevailed. The absence of recorded strong-motion accelerograms by dense arrays, and the lack of three-dimensional soil and geological characterizations of sites, eventually led to simplified site descriptions, many of which continue to be in use today.

Looking back at numerous studies of site effects, certain characteristics and trends emerge. First, many studies were carried out by prominent seismologists (e.g., Gutenberg, 1957), who usually work only with linear waves with long-period motions (say, longer than ~1 s), small wave amplitudes, and large epicentral distances (e.g., more than ~100 km). Second, engineering contributions to the studies of site effects, in the beginning, used only the amplitudes of peak acceleration (i.e., they did not consider the frequency content of ground motion) and tended to use only the site characterization in terms of the surface soil conditions (with dimensions rarely exceeding ~200 m) (e.g., Seed et al., 1976; Ambraseys et al., 1996; Lee, 2007). This trend continues today. It should not be so, but it is rationalized by the fact that it is expensive and difficult to include deeper site characterization and to use a wider zone surrounding the site (e.g., on the scale of several hundred meters to several kilometers). Third, with few exceptions, most studies of site effects are based on forward modelling and regression analyses, and they rarely test the significance of the computed regression coefficients and do not test for cross-correlations among the parameters of the model. The soil site-condition variables (which should be important for short-period motions) and the geologic site-condition variables (which are important for intermediate and long-period motion) are correlated by the nature of their formation, and they are usually not considered simultaneously in most regression models. The result is that most scaling methods, which are based on the site conditions and consider only soil-site classification, average out the effects of the geological site conditions and are characterized by large uncertainty in the prediction of spectral amplitudes. Fourth, because most strong-motion data are available for fault-to-station distances in the range from about 25 to 100 km, essentially all published regression models reflect the trends in the data for this distance range. Since the significant damage to structures occurs mainly within several tens of kilometres from the fault (in the near field), the nature of the site effects and the extent to which they influence the ground motion will be different from what is determined from the regression analyses of the distant recordings, in that they will describe essentially linear and almost-linear site response. Fifth, it is assumed that the site effects are repeatable from one earthquake to the next and that they do not depend significantly on the azimuth, angle of incidence, and amplitudes of seismic waves. However, studies of multiple earthquake recordings at the same strong-motion stations show that this assumption holds at best only about 50% of time, and only at some recording stations (Trifunac et al., 1999; Trifunac and Ivanović, 2003a, b). Sixth, it is very rarely asked whether the parametrization of the site conditions should have been done differently, on the basis of some rational physical considerations (Todorovska and Trifunac, 1998), so that it could be correlated with, and shown to be significant in terms of, the end result (e.g., distribution of damage).

More recently, licensing pressures resulting from the need for consensus building among ground-motion experts, at first in the design of nuclear power plants and then in the revision of the design codes, have resulted in the emergence of group efforts for the development of scaling equations of strong ground motion. On the positive side, this has resulted in increased exchange of ideas and more discussions among the researchers who work on the effects of local site conditions. However, this has also reduced the role of original, individual approaches and has led to the adoption of scaling models, which favour the "average" view rather than the search for the "best" physical models. This consensus building may help to speed up the licensing process, but nature will follow its course, and what individual researchers may not be able to change in the consensus, future earthquakes certainly will. In the following, I will not be guided by any "consensus" views but rather will try to outline how local site effects have been addressed in the past and how we might improve their representation, based on what is known to date.

In summary, the shortcomings of the studies dealing with the effects of site conditions on the amplitudes of strong ground motion are that (1) what are adopted as "site conditions" are often not based on the physical nature of the problem—i.e., on a careful study of the nature of wave propagation through geologic and soil layers—but rather on the heuristic description of the information that a geologist and an engineer can gather from published maps and through field observation; (2) the form of the regression equations that are used to describe the trends is often not based on the nature of the problem but rather on mathematical forms that lead to manageable regression analyses; and (3) the formulation is essentially linear (Trifunac, 1990). Consequently, the results and lesions from such studies are valid only at a certain distance from the earthquake faults, where nonlinearities in the site response are absent or small. In the near field, where large motions cause damage and destruction of structures, and where the soil experiences large, nonlinear deformations, these results cease to predict the outcome, and new methods must be developed to provide characterization of strong-motion amplitudes for engineering applications. In this paper, I will discuss some of these alternatives and give examples of the phenomena that need to be modelled, using examples from selected earthquake studies.

2. The Linear Approach

The linear (transfer-function) representation of strong ground motion can be viewed in the frequency domain as

$$O(f) = E(f)P(f)S(f), \tag{1}$$

where f is frequency, $O(f)$ and $E(f)$ are, respectively, the Fourier spectra of the motion at a site and at the earthquake source, and $P(f)$ and $S(f)$ are the transfer functions of the propagation path and of the local site effects. This representation is meaningful for epicentral distances that are large relative to the source dimensions, when the earthquake source can be approximated by a point source. In the near field, the small distance between the site and the large area of the rupturing fault results in geometrical nonlinearities, which are caused by the spatial distribution of wave arrivals from different segments of the fault surface. Thus, in the near field, Eq. (1) ceases to be valid because $E(f)$, $P(f)$, and $S(f)$ become complex, geometrically nonlinear functions of the space coordinates. While $O(f)$ could be represented by an equation related to Eq. (1), it would have to be in the form of an integral over the fault surface, with $P(f)$ and $S(f)$ being functions that depend upon the geologic environment and on the site location. Further, $E(f)$ would have to include contributions from near-field terms in the representation of the source radiation ($1/r^2$ and $1/r^4$ terms, where r is the distance between the site and a point on the fault surface; Haskell, 1969; Trifunac, 1974). With $\varphi_j r_i R_{i,j} R/a \rightarrow \infty$, where R is the epicentral distance and a is some representative size of asperities on the fault surface, Eq. (1) asymptotically becomes linear (geometrically, since there is no need to integrate over the fault surface) and can represent the site and the propagation effects well.

For two sites having different site conditions and a separation distance that is small relative to a large epicentral distance, it is reasonable to assume that their motions will differ mainly due to the differences in $S(f)$, while their $P(f)$ can be assumed to be nearly the same. This reasoning has evolved into a framework for most theoretical and empirical studies of the effects of site conditions on the amplitudes of strong ground motion (Kanai, 1983; Trifunac, 1990). In the following, this approach will be illustrated through several representative studies.

In equation (1) $S(f)$ models the site effects in general and can represent the geological site effects, the soil site effects, both of those together, or the surface topography, and it may include other site characteristics that may be relevant. In this paper, I discuss the role of $S(f)$ only as representing the geological site effects, soil site effects, or both of those together, and I do not consider examples of any other aspect of site dependence. While using this approach, it is important to define precisely and a priori what is included in $S(f)$ to avoid ambiguity in interpreting the end results. It is remarkable how many papers, even some written by very experienced researchers, use imprecise site descriptions (e.g., by mixing the geological and soil site conditions), only to arrive at wrong conclusions (Aki, 1988).

2.1. GEOLOGICAL SITE CONDITIONS

Considering the size of geological inhomogeneities, the distances travelled by strong-motion waves, and the wavelengths associated with the frequencies of interest in earthquake engineering (0.05 to 50 Hz), it is clear that the local geologic conditions play a prominent role in determining the local site amplifications (Trifunac, 1976a, 1978, 1979; Trifunac and Anderson, 1977, 1978a,b).

In this paper, I use "geological site conditions" to represent the binary interpretation of the site conditions as can be determined from geological maps ($s = 0$ for sites on sediments, and $s = 2$ for sites on the basement rock). Trifunac and Brady (1976) show examples of how the geological site descriptions can be converted to $s = 0$ or 2, and to $s = 1$ for "in-between" sites, which are near the contact of sediments with basement rock, or which are in a complex setting that does not allow unequivocal and simple site description. Sites on sediments ($s = 0$) can further be described by their thickness (h) above the basement rock (Trifunac and Lee, 1978, 1979). The nature of the geological site conditions, as described by s and/or h, involves a scale that is measured in kilometers (Trifunac, 1990).

Before the advent of digital computer, analyses of the amplification of ground motion, were performed by manually measuring the recorded peaks of instrument response. Periods of motion were evaluated from the frequency of zero crossing or by approximating individual peaks by half-sine pulses. For example, Reid (1910) found amplification of 1 to 2 for sandstone, 2 to 4 for sand, and 4 to 12 for man-made fill and marsh. For seismometer response to local earthquakes, with periods of the peaks in the range from 0.5 to 1 s, Gutenberg (1957) analysed recordings from 25 temporary stations on sediments and one reference station on basement rock. He found amplification of about 2 to 3 on deep sediments. Similar trends were later observed by Borcherdt (1970), Borcherdt and Gibbs (1976), and Campbell and Duke (1974). After digital data processing became possible and the recorded strong-motion accelerations could be corrected and integrated to give velocities and displacements, Trifunac and Brady (1976) and Trifunac (1976a,b) extended this work to all peaks of strong ground motion and found excellent agreement with the results of Gutenberg (1957) for periods longer than about 0.5 s and for peak velocities and peak displacements. However, they found a reversal of this trend for peak accelerations (i.e., for strong-motion amplitudes at high frequencies) and showed that the peak accelerations recorded on basement rock are comparable to or larger than the peaks recorded on sediments and on alluvium. The work of Trifunac and Brady (1976) brought out the significance of the frequency-dependent nature in the amplification by local site effects.

The age of sediments (and of rock) under the recording station also influences the amplitudes and the duration of strong motion. It can be shown to correlate well with the geologic site classification ($s = 0$, 1, and 2) and can be used as an additional variable in the regression models. Studies of how the age of site deposits interacts with other site parameters and contributes to the overall duration of strong motion are described in Novikova and Trifunac (1995). Studies of how the age of local site deposits contributes to spectral amplitudes in regression equations that also include the geologic and soil site parameters have not been performed thus far.

2.2. SOIL SITE CONDITIONS

Characterization of the soil site conditions involves a depth scale, which originally extended to about 200 m (deep, cohesionless soils, as in Seed et al., 1976, but which in more recent studies has been reduced to only 30 m below the surface (Chiou et al., 2008). Because of this small thickness, soils can be expected to contribute mainly to the high-frequency, linear changes in the incident seismic waves, but because of their low stiffness and nonlinear behaviour they can play a significant role at all frequencies of the observed motions. The soil site conditions introduced by Seed et al. (1976) involve four groups: “rock” ($s_L = 0$, for sites with a shear-wave velocity of less than

800 m/s and a thickness of less than 10 m), stiff soil sites ($s_L = 1$, with a shear-wave velocity of less than 800 m/s and a soil thickness of less than 75 to 100 m), deep soil sites ($s_L = 2$, with a shear-wave velocity of less than 800 m/s and a thickness of between 100 and 200 m), and soft-to-medium clay and sand ($s_L = 3$) (where the notation $s_L = 0$, 1, 2, 3 is as introduced and used by Trifunac, 1987, and Lee, 1987).

Categorical variables, which describe the shallow soil site conditions in terms of the average shear-wave velocity $\bar{v}$ in the top 30 m of soil, were at first defined as: A for $\bar{v} > 750$ m/s, B for $360 < \bar{v} < 750$ m/s, C for $180 < \bar{v} < 360$ m/s, and D for $\bar{v} < 180$ m/s. With minor variations, these categorical variables continue to be refined as more data become available (Chiou et al., 2008).

Trifunac (1987) showed that the local soil and geologic site conditions must be considered simultaneously in the empirical scaling of strong-motion spectral amplitudes, and he presented a family of such scaling equations. Lee (1987) extended this work to the scaling of pseudo-relative velocity spectra. In searching for the most stable equations, and in order to find the type of regression analysis that is most suitable for such scaling, eight different models were considered, two pairs for direct scaling in terms of the local geologic conditions modelled by the depth of sediments, and two pairs for scaling in terms of the simple geologic site conditions ($s = 0$, 1, and 2). Each pair consisted of one set of equations for scaling in terms of earthquake magnitude and one set for scaling in terms of the site intensity. Corresponding to these four models, in which the simultaneous effects of both local soil and local geologic conditions were considered, a set of four other models with two-stage regression was also analysed, first with respect to all scaling parameters, including the local geologic conditions, and then with respect to the residuals in terms of the local soil conditions only. These regression analyses are too complex to review here, but for the purpose of this paper it is sufficient to note that all local soil and geologic site effects can be described by the coefficient functions of the period of motion T. These functions, representing amplification, typically are small or negative for short periods and positive for intermediate and long periods.

It is noted here that both the derived scaling functions for site amplification in terms of the geological site parameters (s and h) and the soil site parameters (s_L), as well as the corresponding parameters in the site database, are correlated. This is to be expected because of the nature of the creation, transport and the deposition of soil materials. For the data set used by Trifunac (1987), there were many (33%) deep-soil sites ($s_L = 2$) over sediments ($s = 0$, or $h > 0$) and 10% "rock"-soil sites ($s_L = 0$) over basement rock ($s = 2$, or $h = 0$). There were, however, also many (27%) stiff-soil sites

($s_L = 1$) over sediments ($s = 0$, or $h > 0$) and 8% "rock"-soil sites ($s_L = 0$) over intermediate geologic sites ($s = 1$) (Trifunac, 1990). Consequently, the use of regression models, which describe the site conditions in terms of only soil or geological site parameters, averages out the dependence upon the site parameter, which is not used in the analysis. This leads to erroneous prediction of the amplification by local site conditions, and, using the distribution of the site conditions in the study by Trifunac (1987) as an illustration, these erroneous predictions occur about 40% of the time. In view of this, it is remarkable how many studies still continue to develop scaling equations using only the soil site classification variables (e.g., Abrahamson and Silva, 1997; Ambraseys et al., 2005a,b; Boore et al., 1997), as if all strong-motion data has been recorded under identical geologic site conditions!

Here, I discuss only the results based on the s, h, s_L, and $\bar{v}$ (or A, B, C, and D) site parameters. Examples of other site-specific parameters that have been considered in the analysis of the local site effects on the amplitudes of strong motion are described in Rogers et al. (1985). They studied the role of nine geotechnical parameters (mean percentage of silt and clay, thickness of Quaternary, age, thickness of Holocene, depth to water table, textural type, depth to crystalline basement, depth to cementation, and mean shear-wave velocity) and found that in addition to void ratio and shear-wave velocity the thickness of unconsolidated sediment and the depth to basement rock are significant parameters controlling overall site effects. In another, related study, Goto et al. (1982) described the relationship between the site effects and the blow counts (N-value).

2.3. $R_{I,J}$, R_I AND φ_J

The above-discussed geological and soil site conditions represent a characterization of the recording site as a "point on the ground surface" and ignore the horizontal extent and geometry of those conditions. In a series of papers on the duration of strong ground motion, Novikova and Trifunac (1993a,b, 1994a,b, 1995) introduced the additional site- and earthquake-specific variables $R_{i,j}$, r_i and φ_j. $R_{i,j}$ represents the effective horizontal distance (in km) from the site (j) to a basement outcrop (i), which is at distance r_i from the earthquake epicentre and is capable of reflecting strong-motion waves from the source back toward the site (j), thus contributing to prolongation of strong ground motion (Fig. 1). φ_j is the angle containing those outcrops, as seen from the recording station (j), and is evaluated separately for each earthquake. Both $R_{i,j}$ and φ_j were found to contribute significantly to duration of strong motion and were therefore adopted as new site-specific variables in the empirical scaling of the duration of strong shaking. Through prolongation

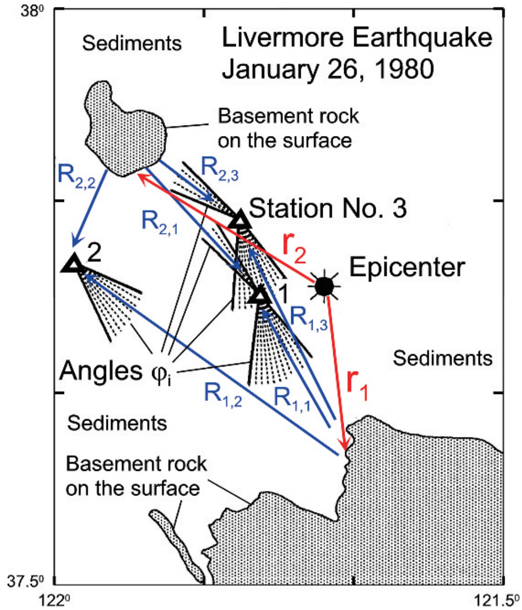

Figure 1. Parameters for horizontal reflections: the angles φ_j subtended at the recording stations by the surface of the rocks from which reflections occur, and the distances r_i and R_{ij} (from Novikova and Trifunac, 1993b).

of shaking, these site parameters will also affect the spectral amplitudes of strong motion, but the empirical studies for their inclusion in the scaling models of spectral amplitudes have yet to be carried out.

2.4. PERCENTAGE OF DISTANCE TRAVELLED THROUGH BASEMENT ROCK – P

Between the source and the recording station, the strong-motion waves encounter different configurations and a number of sedimentary basins (Fig. 2). At each interface, complex reflections and refractions occur, and many new waves are generated. To characterize such effects on the amplitudes and on the duration of strong shaking, one can begin by considering the percentage of the wave path, from epicentre to the recording site, covered by the basement rock, for each path type separately. Then, $p = 100$ represents a path entirely through rock, and $p = 0$ is for the path only through sediments. It has been shown that p is a significant variable and that the scaling equations can be developed for a family of different paths (Lee and Trifunac, 1995; Lee et al., 1995; Novikova and Trifunac, 1995).

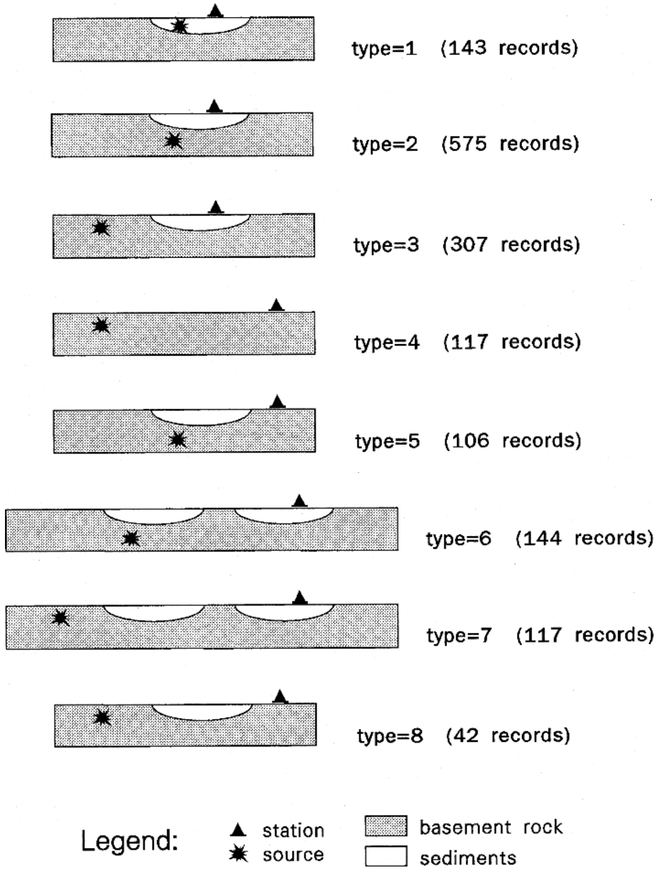

Figure 2. A schematic representation of the propagation path types. For each type the number of acceleration records, which could be used in the regression analyses is shown in the brackets (from Novikova and Trifunac, 1995).

2.5. EXPERIMENTAL METHODS

One approach for estimation of the effects the local soil and geological site conditions have on the amplitudes of strong motion assumes that those effects can also be seen during other forms of excitation. This has led to studies of microtremors, microseisms and of small earthquakes preceding and following (i.e., aftershocks) the damaging earthquakes.

2.5.1. *Microtremors*

During the 1930s and 1940s, Kanai (1983) promoted the measurement of microtremors as a vehicle for experimental estimation of local site effects.

Specifically, he used microtremors to estimate the "predominant site period" and proposed procedures for estimation of the local site effects. Numerous papers have been published about this approach, but successful procedures capable of predicting the amplification during strong earthquake shaking are yet to be formulated. Comparisons of earthquake and microtremor measurements, of the distribution of strong-motion amplitudes, and of the site-predominant periods in California did not produce useful results (Udwadia and Trifunac, 1973). A comparison of the spatial distribution of strong-motion amplitudes and the distribution of damage following the 1994 Northridge, California earthquake with the distribution of amplitudes of long-period microtremors was also not successful (Trifunac and Todorovska, 2000a). In contrast, the use of microtremors in the measurement of structural properties has been very successful (e.g., Ivanović et al., 2000), which suggests that more advanced analysis procedures may yet be developed to make microtremors useful in the estimation of the amplification properties of local site conditions.

2.5.2. *Small earthquakes and aftershocks*

Because destructive earthquakes occur infrequently, many attempts have been made to use the recordings from smaller earthquakes and from aftershocks to predict the amplification of waves by local site conditions. Most of this work is based on the wave amplitudes, which are one-to-several orders of magnitude smaller than the amplitudes of strong shaking. An example of what can be learned from several comprehensive aftershock studies of one earthquake can be found in the paper by Trifunac and Todorovska (2000b). They review three studies of amplification based on the recordings of aftershocks of the Northridge earthquake (Gao et al., 1996; Hartzell et al., 1996; Field and Hough, 1997) and one study of amplification based on four local earthquakes (1971 San Fernando, 1987 Whittier-Narrows, 1991 Sierra Madre, and 1994 Northridge, all in California) by Harmsen (1997). Trifunac and Todorovska conclude that (1) the aftershock studies could not consider longer-period motions (0.2–2 Hz), which contribute to the damaging energy, and (2) that within the current (linear) methods of analysis of aftershock data the results are not useful for prediction of site amplification and of the nonlinear and damaging nature of strong motion within 25 to 30 km from the Northridge fault. For sites further than about 30 km from the fault, where the peak ground velocity was smaller than 15 to 20 cm/s, predictions of the amplification by the local site conditions based on small earthquake and aftershock studies led to fair agreement with the amplifications observed during the main event.

3. Nonlinear Site Response

There are many different signs that the large strong-motion amplitudes in the near field lead to nonlinear response of soil and sedimentary deposits near the surface. The evidence can be seen in the records of strong motion, which show saturation of peak amplitudes, shifting, broadening, and amplitude reduction of the spectral peaks. It can also be seen in the near field, for example, as permanent deformation of surface soil, movement of soil blocks, landslides, and liquefaction. In the following, we discuss a few examples that are mainly associated with the evidence based on recorded motions.

3.1. SATURATION OF PEAK AMPLITUDES

We illustrate the saturation of peak amplitudes by the recorded motions during the 1994 Northridge, California earthquake. Figure 3 shows the nonparametric attenuation functions for peak accelerations at "soft" (C) and "hard" (A and B) soil sites for horizontal (solid lines) and vertical (dashed lines) peak amplitudes, derived by smooth interpolation through the recorded values and plotted versus shortest distance to the map view of the rupture surface. It shows that the horizontal peak accelerations on "soft" sites became saturated in the range between 0.4 and 0.6 g for distances less than about 25 km. It also

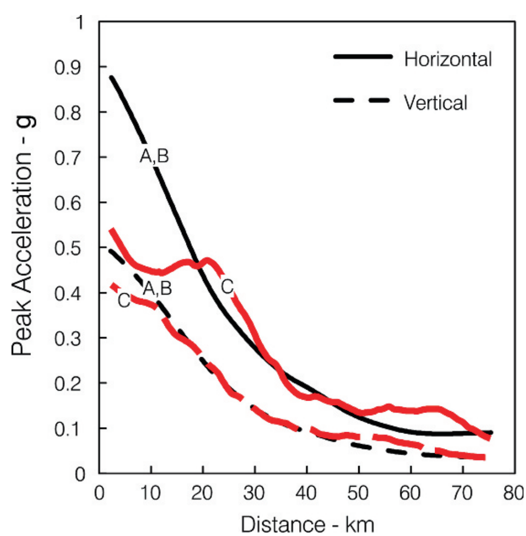

Figure 3. onparametric attenuation functions for peak acceleration at "soft" (C) sites, and "hard" sites (A and B), for Northridge earthquake, and horizontal (solid lines) and vertical (dashed lines) components of motion.

shows that the horizontal peaks at "hard" sites, as well as the vertical peaks at "soft" and "hard" sites, did not reach saturation during this earthquake. For the sediments and soils in the San Fernando Valley (Trifunac and Todorovska, 1998a), this shows that a noticeable reduction of recorded horizontal peak accelerations occurs when the strain in the soil exceeds 10^{-3}, at sites with $\overline{v} < 360\,\mathrm{m/s}$ (C sites). In the San Fernando Valley, during the Northridge earthquake, the area where the recorded strain exceeded 10^{-3} was limited to distances less than 15–20 km from the fault (Trifunac and Todorovska, 1996). Within the same distance range from the fault, there were numerous and unambiguous signs of large nonlinear soil response (EERI, 1995).

3.1.1. *Recurrence and shifting of predominant peaks*

To predict site-specific ground motion during future earthquakes at the site of a structure, analyses of the soil and geology surrounding the site are carried out. The site is usually modelled by parallel layers, with physical properties measured by different *in situ* methods. These models are next used to estimate the site-specific transfer functions (for linear response) or to evaluate nonlinear site response (for large strong-motion amplitudes) via numerical simulation. It is assumed that the site properties do not change with time or with the direction of wave arrival. Also, it is usually assumed that the overall amplification can be modelled by vertically incident shear waves in a stratum with parallel layers, even though it is known that a significant part of the recorded strong-motion energy is propagated to the site by surface waves (Trifunac, 1971a).

Two- and three-dimensional (2-D, 3-D) inhomogeneities at the site lead to shifting, disappearance, and reoccurrence of the spectral peaks in the site-specific linear transfer functions. This is caused by interference, focussing, scattering, and diffraction of waves in the irregular medium surrounding the site (Trifunac, 1971b). Even when the problem may be described by linear material properties, the irregular site geometry contributes to complex changes in the transfer functions, which depend in a nonlinear manner upon the incident angle and the azimuth of wave arrivals. These changes depend also upon the epicentral distance and the 3-D geological inhomogeneities along the propagation path.

Sands tend to settle and densify when subjected to strong shaking (Lee and Albaisa, 1974; Tokimatsu and Seed, 1987). If the sand is saturated and there is little or no drainage, the earthquake shaking can lead to excess pore pressure, and settlement follows as the excess pore pressure dissipates. The settlement can occur instantaneously or within about a day following the shaking. Settlement from earthquake shaking also occurs in dry sands. One of the consequences is compaction, which is accompanied by an increase in the effective shear modulus. The implication for analyses of strong ground motion is that, after settlement, the site-specific peaks in the spectra of recorded motions can shift toward shorter periods. Dynamic compaction of soil following strong shaking will thus result in a “stiffer” site for shaking by waves from the aftershocks. Aftershocks have a small source area, and consequently the pencils of wave arrivals at the site are narrow. All of this may lead to more-coherent high-frequency motions and result in larger high-frequency amplitudes of spectra of recorded motions. In contrast, the main seismic events have extended source areas, are the result of the fracture of many asperities, which are randomly distributed in time and space, and produce waves that propagate along different paths toward the site. This will lead to less-coherent high-frequency signals and apparent “reduction” of the high-frequency spectral amplitudes, which may be misinterpreted as resulting from nonlinear soil response (Hartzell, 1998).

The rare occurrence of intermediate and strong earthquakes rules out the possibility of evaluating site-specific transfer functions for design directly from representative strong-motion earthquake recordings. As already noted, this lack of real data has led to the idea that recording and analysing weak motions (from microtremors and microseisms) will help estimate the site-specific transfer functions experimentally (Kanai, 1983). However, field tests in El Centro, California did not show any similarity of spectra of recorded earthquakes and of measured microtremors at a site because the recorded waves (1) are of a different type, and (2) have different propagation paths (Udwadia and Trifunac, 1973). One-dimensional, equivalent, linear numerical-simulation studies have also concluded that “the use of small earthquake records as the basis for evaluating site response during strong earthquakes may be misleading” (Idriss and Seed, 1968).

In spite of this negative evidence, site-specific response is often investigated by comparing recorded strong motions during an earthquake with weak motions during subsequent aftershocks. The basic premise is that Fourier amplitude spectra of recorded motions can be represented by a product, as in Eq. (1). If a site repeatedly amplifies PSV amplitudes at certain frequencies, structures at the site with similar natural frequencies will also experience larger response. Therefore, to find out how often these peaks recur during excitation by different earthquakes it would be useful to search for the repeated occurrence of local peaks in the Fourier amplitude spectra that also appear as strong and well-defined peaks in the PSV spectra (Trifunac et al., 1999; Trifunac and Ivanović, 2003a,b).

Figure 4a shows by solid dots (“obvious” peaks) and open circles (“not-so-obvious” peaks) the periods of spectral peaks that can be identified during 41 events (listed according to the amplitude of their peak velocity, shown on

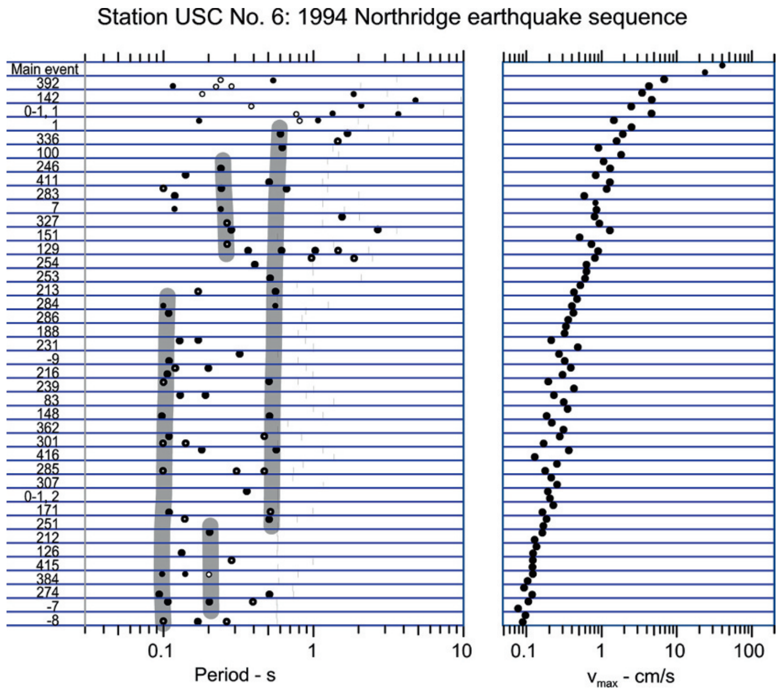

Figure 4a. Periods of identified peaks of Fourier spectra (left) and of peak ground velocity (right) for 41 records of the 1994 Northridge earthquake and its aftershocks, recorded at station USC 6 (from Trifunac et al., 1999).

the right) recorded at station USC 6 in the San Fernando Valley (Anderson et al., 1981) during the 1994 Northridge earthquake (main event) and 40 of its aftershocks that triggered the accelerograph at this station. Wide gray lines mark the periods near 0.10, 0.20, and 0.55 s, which reappear in many records. Two important characteristics of this plot should be noted. First, the site-characteristic peaks are not present in all recordings. Considering all of the sites studied in this manner thus far (Trifunac et al., 1999; Trifunac and Ivanović, 2003a,b), the site peaks occur again at most about 50% of time, but usually less often. Second, the spectral peaks shift to longer periods or completely disappear for motions with peak ground velocity larger than about 10 cm/s. Figure 4b shows a similar plot, but with the contributing events arranged in the chronological order following the main (Northridge) event. It shows a clear shift of the period of the peak, from about 1 s (during the main event) toward 0.3 s 10 min later, during events 9 and 20. The right side of this plot shows the approximate values of strain in the ground, in the range between 10^{-5} and 10^{-3}. To illustrate the long-term (seven years) variations

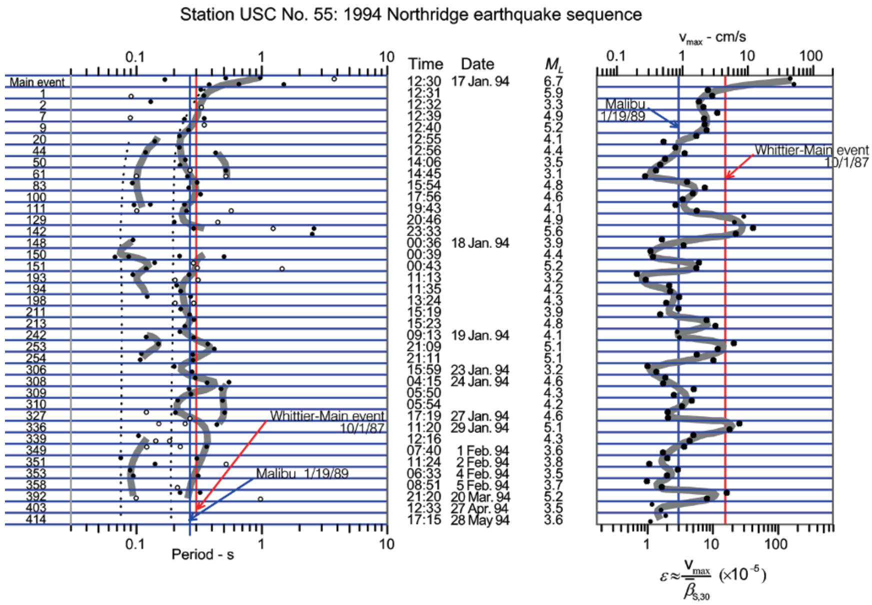

Figure 4b. Periods of identified peaks of Fourier amplitude spectra (left) and of peak horizontal ground velocity $v_{\max}$ (right) for 41 records of the 1994 Northridge earthquake and its aftershocks, recorded at station USC 6, arranged in chronological order. The bottom-right scale shows an estimate of peak strain $v_{\max}/\beta_{s,30}$, where $\beta_{s,30}$ is the average shear-wave velocity in the top 30 m of soil. The periods and the peak velocities for two preceding earthquakes are shown by vertical lines (1987 Whittier Narrows and 1989 Malibu) (from Trifunac et al., 1999).

in the site strain amplitudes, the strains during the Malibu (1/19/89) and Whittier-Narrows (10/1/87) earthquakes are also shown. It can be seen that at this station the layer stiffness returns to its original value during several early aftershocks.

Figures 4a and b, together with other such figures we have studied (Trifunac et al., 1999; Trifunac and Ivanović, 2003a,b), show that it is possible to measure the site-characteristic peaks by analysis of multiple recordings at a station when the motions are small (i.e., peak velocity is less than 5–10 cm/s). However, the resulting peaks do not appear with every excitation, and for the cases we studied they appear at most about 50% of time. With peak ground velocity exceeding 10 cm/s, site-characteristic peaks begin to disappear, and as the peak ground velocity approaches and exceeds 100 cm/s (Fig. 5) essentially all peaks disappear (Trifunac and Ivanović, 2003a). This is consistent with the conclusions of Gao et al. (1996), Hartzell et al. (1996), and Trifunac and Todorovska (2000b).

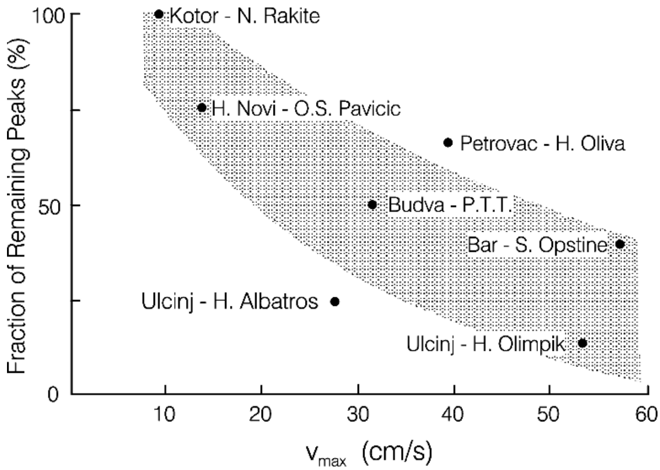

Figure 5. Fraction of identified site-specific peaks that remain in the data set, as peak ground velocity increases from 10 to 60 cm/s. At 60 cm/s and above, 60% to 90% of all site-specific peaks disappear due to nonlinear response of the soil (from Trifunac and Ivanović, 2003a).

3.2. MOVEMENT OF SOIL BLOCKS

Many observations in the epicentral regions (cracks in the pavement, buckled curbs, and concentrations of breaks in the pipes of the water distribution system) show that the near-surface soil does not move as a continuum but rather as a collection of blocks of material moving one relative to the other. This suggests that a radically different and new approach to modelling the effects of the local soil on strong ground motion and damage—and consequently for microzonation of metropolitan areas—is needed to predict the effects of damaging earthquakes.

Trifunac and Todorovska (1998b) studied simultaneously the spatial distribution of damaged (red-tagged) buildings (RTBs) and of pipe breaks following the 1994 Northridge earthquake, and they discovered that the areas with RTBs do not overlap with the areas with a large concentration of pipe breaks, except where the ground shaking was very severe (i.e., peak ground velocity exceeding about 150 cm/s). Their interpretation is that typical buildings (i.e., wood-frame buildings, which represented 84% of all buildings that received red tags) suffered less damage where the soil response was not linear. They defined so-called "gray zones" with somewhat fuzzy boundaries, but such that, wherever possible, they included the RTBs and excluded the pipe breaks. A model that could predict the location of these gray zones has not yet been formulated, but the possibility that such zones exist, in which buildings are more prone to damage because of specific features of the site geology and soil, is very significant for seismic hazard mapping and deserves detailed

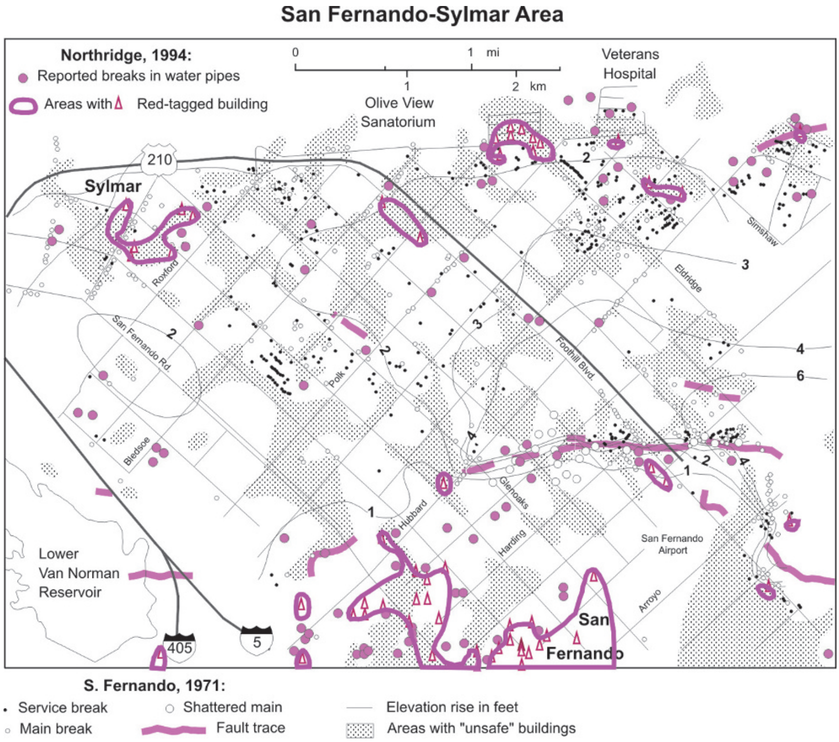

Figure 6. Sylmar–San Fernando area: overlay of the “gray zones” (for all “unsafe” buildings) and locations of pipe breaks for the 1971 San Fernando earthquake with the “gray zones” for the 1994 Northridge earthquake (from Trifunac and Todorovska, 2004).

further investigation. The authors then studied the distribution of RTBs during the 1971 San Fernando earthquake and discovered that it is possible to construct the gray zones so that they include the damaged buildings from both earthquakes while excluding the sites of the pipe breaks, also during both earthquakes (Trifunac and Todorovska, 2004). An example illustrating this is shown in Fig. 6. It can be seen that the buildings severely damaged by the Northridge earthquake occurred essentially within the gray zones defined for the San Fernando earthquake, which had occurred 23 years earlier. This figure also shows the gray zones for both earthquakes. It can be seen that in the San Fernando–Sylmar area the shaking from the Northridge earthquake “extended” the boundaries of the gray zones drawn for the San Fernando earthquake, but in a manner consistent with the principle that the gray zones do not include sites with breaks in the water pipes.

The aim of Trifunac and Todorovska’s (2004) paper was to find (1) whether the gray zones (first discovered for the 1994 Northridge earthquake) existed also for the San Fernando earthquake, (2) whether and to what degree the gray zones for both earthquakes overlapped, and (3) what determines the location of the gray zones—e.g., the patterns and distribution of strong-motion amplitudes, the distribution of weaker buildings, or some other site characteristics. For the same population of buildings, two earthquakes with similar size and mechanism, and occurring within the same area, would be expected to produce similar effects. However, the Los Angeles metropolitan area grew between 1971 and 1994, and these two earthquakes neither had the same focus nor the same source mechanism. Thus, comparing the damage from these two earthquakes was not a simple task. Nevertheless, Trifunac and Todorovska's (2004) paper shows that the overall trends for both earthquakes appear to be stable, significant, and consistent. The conclusion reached is that the formation of the gray zones is mainly governed by the local soil and geologic conditions at the site, which do not change significantly during the life of a typical building (50–100 years). The implications of these observations are important, both for the future development of seismic zoning methods and for the characterization of site-specific models, with the goal being the prediction of strong motion in the near field when a local site experiences large, nonlinear deformations.

The above examples of the separation of the gray zones (with damaged buildings) from the areas with the breaks in the water pipe system, for San Fernando 1971 and Northridge 1994 earthquakes is not unique. This type of separation can and should be analysed and interpreted following any earthquake for which sufficiently detailed data exists. We only have to search for such data and interpret it (Trifunac, 2003).

3.3. NUMERICAL MODELS

Numerical methods (finite-element and finite-difference) have been used for studies of the irregular geometry of sediments and soil layers and to explore the characteristics of nonlinear response. The majority of the published papers address only one-dimensional wave propagation in simple models (e.g., Gičev and Trifunac, 2008). These studies show the complexity and the multitude of possible outcomes, which are difficult to describe with a few parameters, and thus it is difficult to incorporate them into the engineering regression analyses of recorded strong motion. As with most problems that involve large, nonlinear deformations, the number of possible outcomes becomes large and complex (Trifunac, 2009). It appears at present that we will continue to learn a great deal about the nature of nonlinear site response by investigation of the results obtained by numerical models, but the potential simple breakthroughs for robust engineering predictions can come only from many more recordings of nonlinear motions in the near field.

4. How should the Local Site Conditions be modeled?

The above-reviewed methods for description of the effects the local site conditions have on the amplitudes and spectral content of strong earthquake ground motion can all be categorized into the same group—ad hoc forward representations. In all approaches, an assumption is made with regard to how the local site effects can be modelled (this includes parametric representation for use in regression analyses and representations for numerical response simulations), and the model parameters are selected by trial and error or by a regression analysis. However, after a model has been developed, the relevance of the model is almost never addressed. This lack of the critical tests is common in the selection of the model parameters and assumptions and in the verification of the entire modelling approach. The use of Kolmogorov-Smirnoff and χ^2 tests (Lee, 2002, 2007; Trifunac and Anderson, 1977), for example, is alarmingly rare even in the most recent papers on this subject, and the question of whether the assumptions and the models are relevant with respect to the observed damage from earthquake shaking is almost never present. Many modelling approaches to selecting model parameters to represent the effects of the local site conditions appear logical and pragmatic within the limited selection framework. However, if we are to develop reliable and robust engineering tools, we must also ask the question: Is the result significant and relevant? I will illustrate this by two examples.

4.1. IS THE AVERAGE SHEAR-WAVE VELOCITY IN THE TOP 30 M A RELEVANT SCALING PARAMETER?

Lee et al. (1995), in their regression analyses of peak accelerations of strong ground motion, studied the significance of the shear-wave velocity parameter in two different ways. First, they used the average shear-wave velocity in the top 30 m of soil, and then they considered the categorical variables A, B, C, and D. Simultaneously, they considered the soil-type parameter s_L (= 0, 1, and 2). They used the student t-statistic and found that the soil-type classification (s_L) is significant, while the velocity-type classification (either average shear-wave velocity or the categorical variables A, B, and C) is not significant. They concluded that further use of the average shear-wave velocity in the top 30 m of soil, or of the corresponding categorical variables A, B, C, and D, is not indicated, while the soil-type classification variable s_L is significant and should be included in all regression models of linear strong motion. They commented that the apparent physical explanation of why s_L is significant and why the average shear-wave velocity is not is that s_L included information on the soil depth well beyond the top 30 m.

Novikova and Trifunac (1995) investigated different regression models for prediction of the duration of strong ground motion, with dependence upon (1) the local soil and geologic site parameters, (2) the geometry of the site conditions, and (3) the age of the materials under the recording station. They found that the age of local deposits is a significant site variable and that it should be included in the empirical prediction equations. However, they also found that the contribution of the average shear-wave velocity variable, $\bar{v}$, in the top 30 m is not significant for frequencies below 2.5 Hz and is significant only for the higher frequencies. The variable $\bar{v}$ describes the properties of only a very thin soil layer, the influence of which on the linear amplitudes of waves longer than 30 m should be small.

Castellaro et al. (2008) revisited old data on the relationship between Fourier spectrum amplitudes of recorded acceleration and $\bar{v}$, and discussed the requirements for meaningful regression and the significance tests of the results. They concluded that "in spite of its almost universal adoption as a key parameter in seismic site classification, $\bar{v}$ appears a weak proxy to seismic amplification".

4.2. WHAT CHARACTERIZATION OF SITE CONDITIONS IS RELEVANT?

An important, often-overlooked principle is that a prediction should be evaluated by a comparison of the actual outcome against a prediction published before the event. Post-facto detailed studies do augment our knowledge, but the only true test is a comparison of the outcome with a prediction made previously (Trifunac, 1989; Trifunac et al., 1994). Thus, a model proposed for prediction of the effects that the local site conditions have on the amplitudes of shaking, or better yet on some measure of structural response, should be evaluated by comparison with some future actual outcome. To illustrate this, we correlate a normalized measure of damage with nonlinear site response and consider different descriptions of the local site properties (measured or postulated), as shown in Fig. 7. In this figure, we plot the number of red-tagged (solid points represent seriously damaged) and yellow-tagged (open circles represent moderately damaged) buildings per 1,000 housing units, normalized relative to the area average versus the number of pipe breaks per 1,000 housing units per area average. In simple terms, we are plotting a measure of damage versus a measure of the strain amplitude in the local soil, as seen through a filter of surface geology, average shear-wave velocity in the soil, and two different liquefaction criteria.

In parts (a), (b), (c), and (d) of Fig. 7, we consider four different site characteristics: (1) surface geology, (2) average shear-wave velocity in the top 30 m of soil, (3) liquefaction susceptibility using L.A. maps, and (4) liquefaction susceptibility using U.S. Geological Survey (USGS) maps. For surface

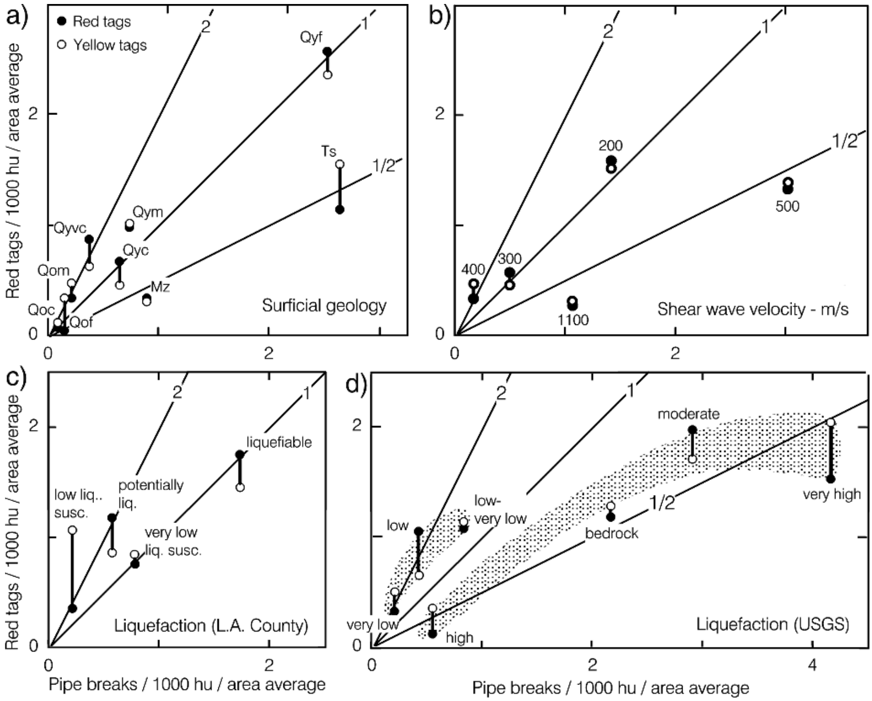

Figure 7. Occurrence of red-tagged buildings (solid points) and yellow-tagged buildings (open circles) versus pipe breaks (both normalized to unit average for the total area of the map) relative to (a) surface geology, (b) surface shear-wave velocity, (c) liquefaction susceptibility based on L.A. County maps, and (d) liquefaction susceptibility based on USGS maps (from Todorovska and Trifunac, 1998).

geology (Fig. 7a), we consider the following: Qyf (fine-grained Holocene alluvium), Qym (medium-grained Holocene alluvium), Qyc (coarse-grained Holocene alluvium), Qyvc (very-coarse-grained Holocene alluvium), Qof (fine-grained Pleistocene alluvium), Qom (medium-grained Pleistocene alluvium), Qoc (coarse-grained Pleistocene alluvium), Ts (Tertiary and pre-Tertiary sedimentary rock), and Mz (Mesozoic and pre-Mesozoic rocks) (Tinsley and Fumal, 1985; Trifunac and Todorovska, 1998a). For average shear-wave velocity in the top 30 m of soil (in Fig. 7b), we consider 200, 300, 400, 500, and 1,100 m/s. In Fig. 7c, we use the liquefaction susceptibility categories as defined in the maps for Los Angeles County: Liquefiable, Potentially Liquefiable, Low Liquefaction Susceptibility, and Very-Low Liquefaction Susceptibility (Leighton and Associates, Inc., 1990)). In Fig. 7d, we use the liquefaction susceptibility categories in the USGS maps: Very High, High, Moderate, Low, Low-Very Low, Very Low, and Bedrock (Tinsley et al., 1985).

Figures 7a and b show that only for Ts and Mz rock sites, and for shear-wave velocities in the soil equal to 500 and 1,100 m/s, there were more pipe breaks than damaged buildings (compared with the respective total area averages). This is due to hillside ground conditions at most of the sites contributing to the data set and the occurrence of landslides. Figure 7d shows that for the sites with “moderate”, “high”, and “very high” liquefaction susceptibility there were proportionally fewer damaged buildings than pipe breaks (compared with the respective total area averages), by approximately a factor of two. This is in excellent agreement with the mechanism for the formation of the “gray zones” (as discussed above) and the passive isolation of single-family, wood-frame dwellings from the incident-seismic-wave energy (Trifunac and Todorovska, 1998b). It can be seen that neither in terms of surface geology nor in terms of the average shear-wave velocity in the top 30 m does the site characterization correlate with the damage to wood-frame residential buildings in the near field. The site characterization in terms of the liquefaction susceptibility (USGS) as described by Tinsley et al. (1985) is the only site characterization in this group of four that is indicated as a useful and significant site-characterization parameter for damaging levels of strong motion. Perusal of the liquefaction susceptibility criteria in Tinsley et al. (1985) shows that the ultimate categorical variables, like “very high” or “moderate”, are derived on the basis of multiple site characteristics and therefore can also describe the relevant site properties for the purposes of amplitude scaling. It can be seen that in the near field, for damaging levels of strong motion, local geological and soil ($\bar{v}$) site conditions cease to be good predictors of the damage to wood-frame structures, while the composite site characterization in terms of the liquefaction susceptibility, as defined in the maps of Tinsley et al. (1985), works reasonably well.

5. Discussion and Conclusions

I have illustrated the contemporary approaches for inclusion of the effects that local site conditions have on the amplitudes of strong ground motion and how those approaches are essentially based on concepts that have evolved from classical linear-wave-propagation theory. While this approach works in the far field, I showed examples of how it ceases to apply in the near field, where the buildings get damaged and where the soil experiences large nonlinear and permanent deformations. I hinted, using an example of a refined site characterization that correlates well with the observed damage (Fig. 7d), that better and more physically meaningful site characterizations can continue to be developed, but this would still leaves us within the traditional “linear” approach for the scaling of strong-motion amplitudes. To go beyond this linear approach and to predict the nature of strong motion in the near-field region that describes the forces on the engineering structures, we must change the entire approach and formulate a new one. This new approach must include all relevant components in the description of the forces acting on a structure. The first step in this direction will require that we abandon the traditional scaling, which is based on only one scalar quantity (e.g., peak acceleration, amplitude of a response spectrum, peak strain, or peak differential displacement) to describe the strong-motion effects on the response of structures. To accomplish this goal, we will have to work with multi-parametric representation and include all relevant components of all forces that act in the near field and that contribute significantly to the response. In the following, we illustrate how this could be done.

With large amplitudes of strong motion, surface soil experiences large, nonlinear response, and ultimately soil failure and liquefaction can lead to large transient and permanent motions. We illustrate this by examples of ground failure that can follow liquefaction: lateral spreading, ground oscillations, flow failure, and loss of bearing strength. *Lateral spreads* involve displacements of surface blocks of sediment facilitated by liquefaction in a subsurface layer. This type of failure may occur on slopes up to 3° and is particularly destructive to pipelines, bridge piers, and other long and shallow structures situated in flood plain areas adjacent to rivers. *Ground oscillations* occur when the slopes are too small to result in lateral spreads following liquefaction at depth. The overlying surface blocks break, one from another, and then oscillate on liquefied substrate. *Flow failures* are a more catastrophic form of material transport and usually occur on slopes greater than 3°. The flow consists of liquefied soil and blocks of intact material riding on and with liquefied substrate, on land or under the sea. *Loss of bearing strength* can occur when the soil liquefies under a structure. The building can settle, tip, or float upward if the structure is buoyant. The accompanying motions can lead to large transient and permanent displacements and rotations, which so far have been neither evaluated through simulation nor recorded by strong-motion instruments.

Consequently, any structure, and in particular all extended structures (e.g., long buildings, bridges, tunnels, dams), in the area where such large nonlinearities in the soil occur, will, in addition to the horizontal components of inertial forces caused by strong earthquake shaking, experience large differential motions and large differential rotations of their foundation(s). Bridge peers or foundations of long buildings supported by soil, which the earthquake has separated into blocks by strong shaking, will be forced to deform, accompanied by large differential motions (translations and rotations) of soil blocks, and they will experience both the inertial and pseudo-static aspects of those motions. At present, we can only speculate about how much larger these motions will be relative to the tilts and angular accelerations and velocities we can estimate from the linear-wave theory. Few observations, however, suggest that those can be orders of magnitude larger than the predictions based on the linear theory (Trifunac, 2008a). For successful design, it will be necessary to prescribe the resulting forcing functions, which will include, in a balanced way, the simultaneous action of all components of possible motion. The description of how to scale those balanced forcing functions can start from principles similar to what we use today for the design of structures crossing an active fault (Todorovska et al., 2007; Trifunac, 2008b). Because the complexity of such motions and the multiplicity of possible outcomes will increase with amplitudes of incident strong-motion waves, specification of the driving forces for design may best be formulated in terms of their distribution functions. This will require systematic and long-range research programs focusing on two key tasks: (1) development of advanced numerical simulation models, and (2) the recording of all six components of strong motion, in the near field, and their analysis and interpretation. Such description of the near-field motion will have to be used in the selection of design forces within distances that are equal to about one source dimension (e.g., up to 20 to 50 km in California) away from the fault. In the far field, we should be able to continue to use the traditional local site parameters to describe the effects of the local site conditions for most design applications.

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