THE NATURE OF SITE RESPONSE DURING EARTHQUAKES

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What is Site Response?

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

$$O(f) = E(f)P(f)S(f) \qquad (1)$$

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 (which we find in the early seismological formulations) is **meaningful only 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. Most studies tend to ignore this and work with Eq. (1) anyway.**

Where are site conditions important?

Understanding of the site conditions is important at all distances, but is particularly needed in the near field where "soft" surface deposits can experience large and complicated nonlinear behavior.

How do we determine the effects of site conditions?

It is best to determine the effects of site conditions from recorded data directly. That can be done only at those distances where the **recorded data is available** and today this is **in the range of epicentral distances between about 25 and 100 km**. Therefore, most published papers on empirical scaling of the site effects describe the trends in the data only in this distance range. Unfortunately, **we often forget this constraint and pretend that our findings are valid at distances smaller than about 25 km, where ground motion can experience large nonlinear response.**

What are the differences between near and far field?

Near field is the distance range surrounding the fault and extends to about one source dimension. Far field applies to distances greater than about ten source dimensions. Theoretically, in the far field, only body (1/r) and surface waves exist. In the near field we also have **near field terms,** in the de Hoop representation theorem, which are large, attenuate **like $(1/r)^2$ and $(1/r^2)^2$**, and **are very powerful** contributors to the response of ground and of structures.

What should be included in the description of "site response" ?

In **linear representations**: Everything that can contribute significantly to the description of physical nature of S(f). This can involve parts of the propagation path, local geometry of sedimentary deposits, surface topography, properties of sediments and of soil at the site, and their horizontal and vertical dimensions.**At preset, the state of the art in the analyses of the site effects is confined only to this view of the problem**. In part this is due to the long held view among seismologists that most amplification phenomena can be explained by linear theory. This view started to change following Northridge 1994, Kobe 1995 and Nisqually 2001 earthquakes.

 In **nonlinear representations** site response will include different nonlinear and failure mechanisms, such as: *Faulting, landslides, liquefaction, settlement, lateral spreads, ground oscillations, flow failures, loss of bearing strength,* for example. Each of these will have to be assigned a probability that it will occur and it will have to be characterized by the motions it can produce (e.g. translations, rotations, strains, curvatures, differential displacements, differential rotations, tilts) with transient and permanent components.

At present, in most research studies and in engineering design applications the site response and site characteristics are described only in the **most elementary (and not satisfactory) fashion** –in terms of the average shear wave velocity in the top 30 meters.

-     Lee et al. (1995) found that the **velocity-type classification (either average shear-wave velocity or the categorical variables A, B, and C) are not significant variables.** They concluded that further use of the average shear-wave velocity in the top 30 m of soil, or of the corresponding variables A, B, C, and D, is not indicated, while the Seed's soil-type classification variable is significant and should be included in all regression models of linear strong motion.

-     Novikova and Trifunac (1995) found that the **average shear-wave velocity variable, in the top 30 m is not significant for frequencies bellow 2.5 Hz** and is significant only for the higher frequencies.

-     Castellaro et al. (2008) concluded that the average shear-wave velocity variable, in the top 30 m "in spite of its almost universal adoption as a key parameter in seismic site classification, appears **a weak proxy to seismic amplification".**

Other site parameters which were used in several studies

Geological Site Conditions

- **At a point**, where the measurements are taken, geological site conditions were first studied systematically by Gutenberg (1957). His observations were later confirmed and extended by Trifunac (1976, 1978, 1979). Both used "geological site conditions" to describe 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 & Lee, 1978, 1979). The nature of the geological site conditions, as described by s and/or h, involves a scale that is measured in kilometres (Trifunac, 1990).

Livermore Earthquake
January 26, 1980
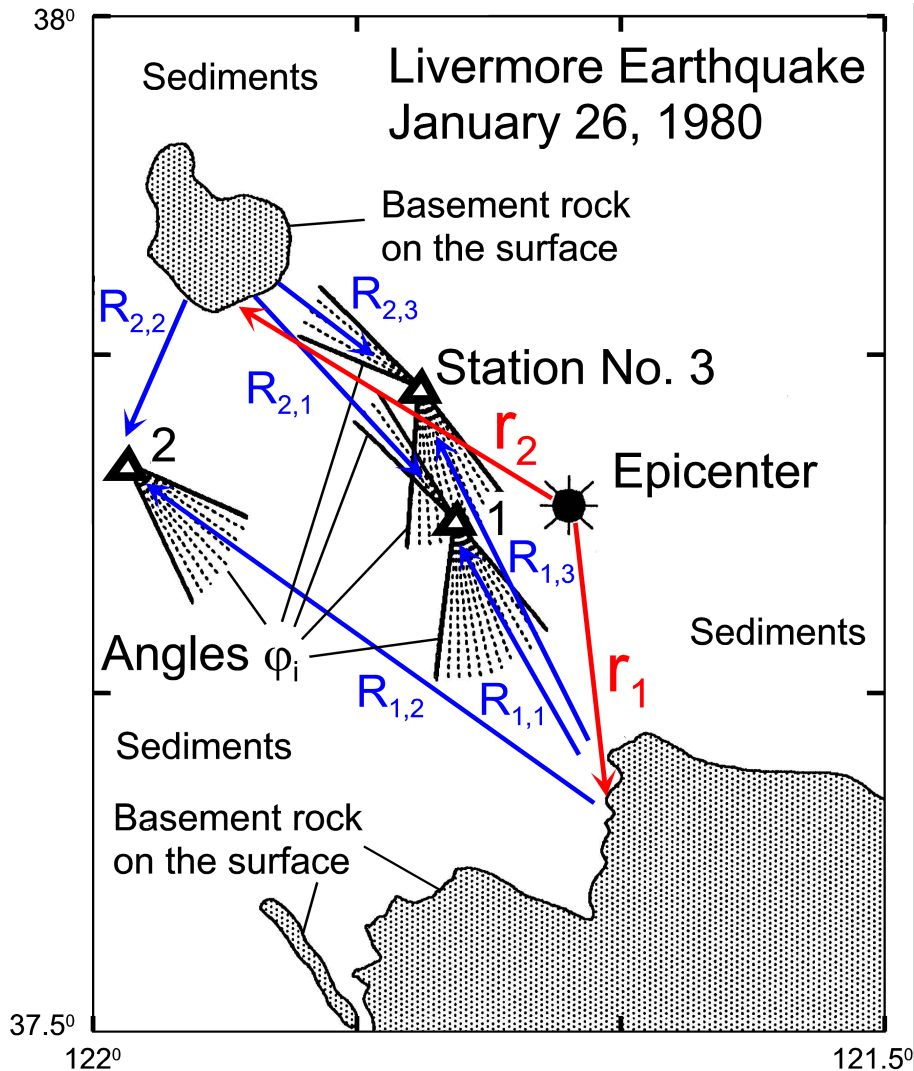
- **In a region containing source and the station** and describe the distances to the surface outcrops of basement rocks which can reflect the earthquake waves back towards station. These "horizontal" geological site variables, first introduced by Novikova and Trifunac (1993), were found to contribute significantly to the 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 of shaking, these site parameters 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.

Legend: ▲ station   basement rock
          ✳ source   sediments
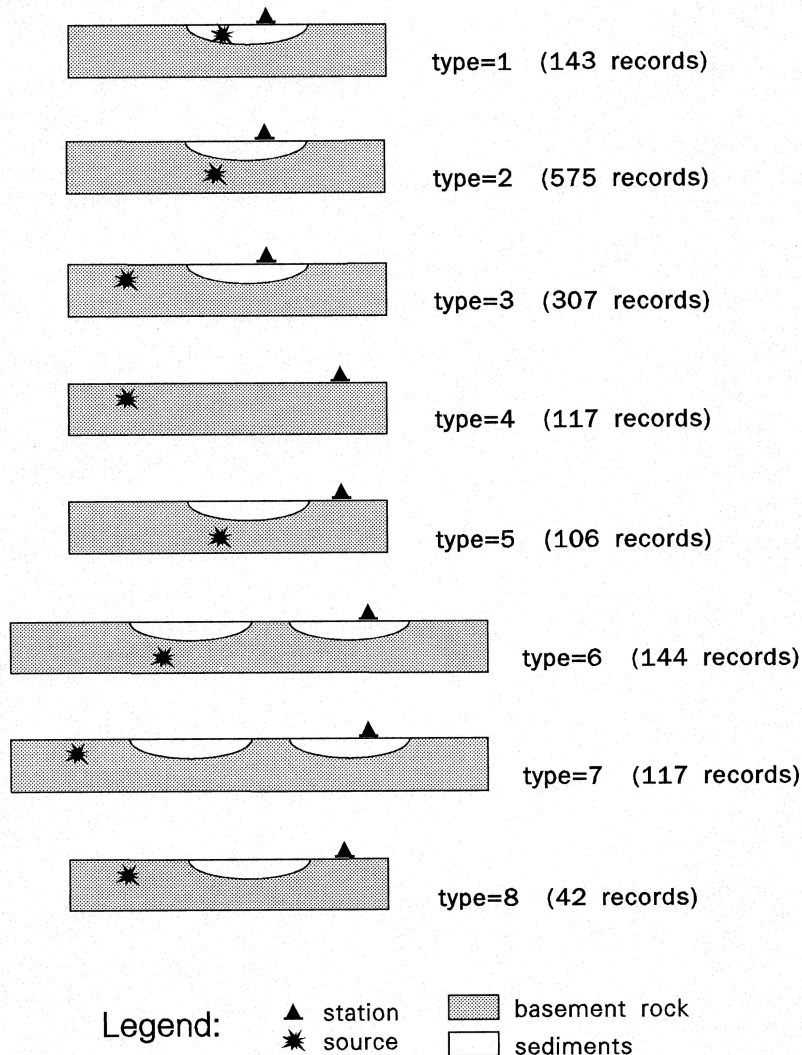
- **_Geological propagation path._** Between the source and the recording station, the waves encounter different configurations and a number of sedimentary basins. At each interface, reflections and refractions occur, and new waves are generated. To characterize such effects on the amplitudes and on the duration of strong shaking, we 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 (type 4), and p = 0 is for the path only through sediments (type1). **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 & Trifunac, 1995; Lee et al., 1995; Novikova and Trifunac 1995).

Soil-type classification.

The soil type classification introduced by Seed et al. (1976) involves four groups: "rock" (= 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 (= 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 (= 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 (= 3) (where the notation 0, 1, 2, 3 is as introduced and used by Trifunac, 1987, and Lee, 1987). Lee et al. (1995), studied the significance of the average shear-wave velocity and of the soil-type classification parameters. They used the student t-statistic and found that the **soil-type classification as defined by Seed et al (1976) is significant descriptor of strong motion amplitudes**, while the velocity-type classification (either average shear-wave velocity in the top 30 m or the categorical variables A, B, and C) is not significant. They concluded that the soil-type classification should be included in all regression models of linear strong motion. They commented that a physical explanation of why soil type classification is significant and why the average shear-wave velocity is not is that the former included information on the soil depth well beyond the top 30 m.

What parameters should be used in empirical scaling models?

Repeated significance tests of the regression scaling coefficient functions show that (1) the geological site parameters (classification s, or depth h), (2) the soil type classification parameters, and (3) the geological path type parameter should all be included simultaneously.

Some of these parameters in the site database, are correlated because of the nature of the creation, transport and the deposition of soil materials, for example. For the data set used by Trifunac (1987), there were many (33%) deep-soil sites over sediments (s = 0, or h > 0) and 10% "rock"-soil sites over basement rock (s = 2, or h = 0). There were, however, also many (27%) stiff-soil sites over sediments (s = 0, or h > 0) and 8% "rock"-soil sites over intermediate geologic sites (s = 1). Consequently, the use of regression models, which describe the site conditions in terms of only soil or only 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 & 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.**

Some observations in the near field

Saturation of Peak Amplitudes. We illustrate the saturation of peak amplitudes by the recorded motions during the 1994 Northridge, California earthquake. This figure 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 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 (Trifunac & Todoovska 1996).
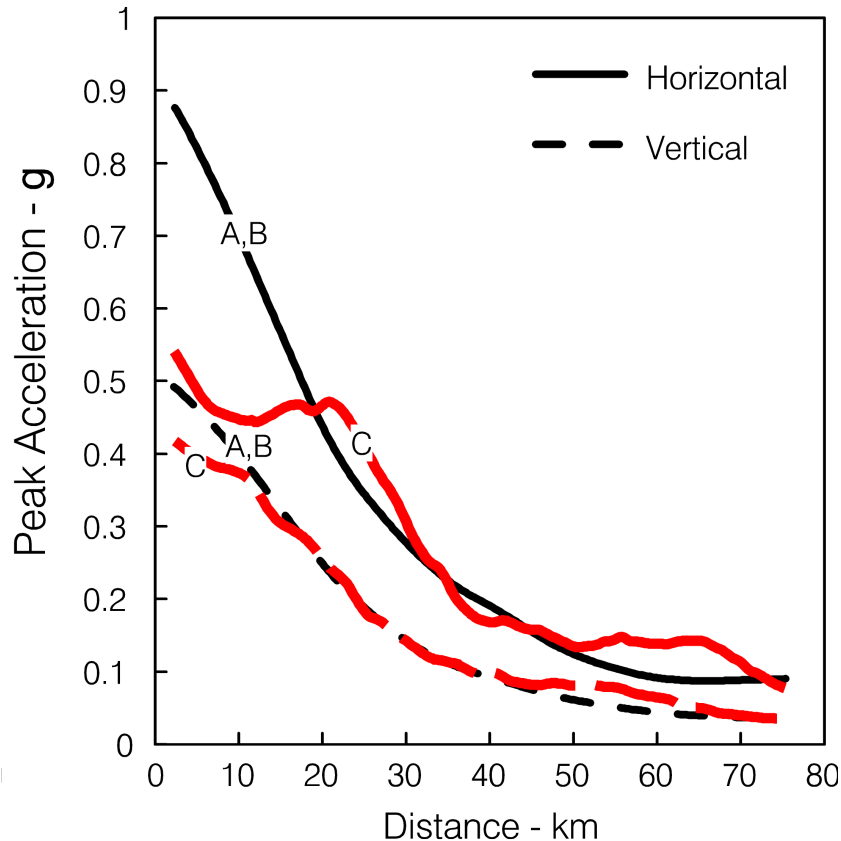
Recurrence and Shifting of Predominant Peaks. Trifunac et al., (1999) have shown that one can measure the site-characteristic peaks by analysis of multiple recordings at a station.

Station USC No. 55: 1994 Northridge earthquake sequence

$$\varepsilon \approx \frac{v_{max}}{\beta_{S,30}} \ (\times 10^{-5})$$
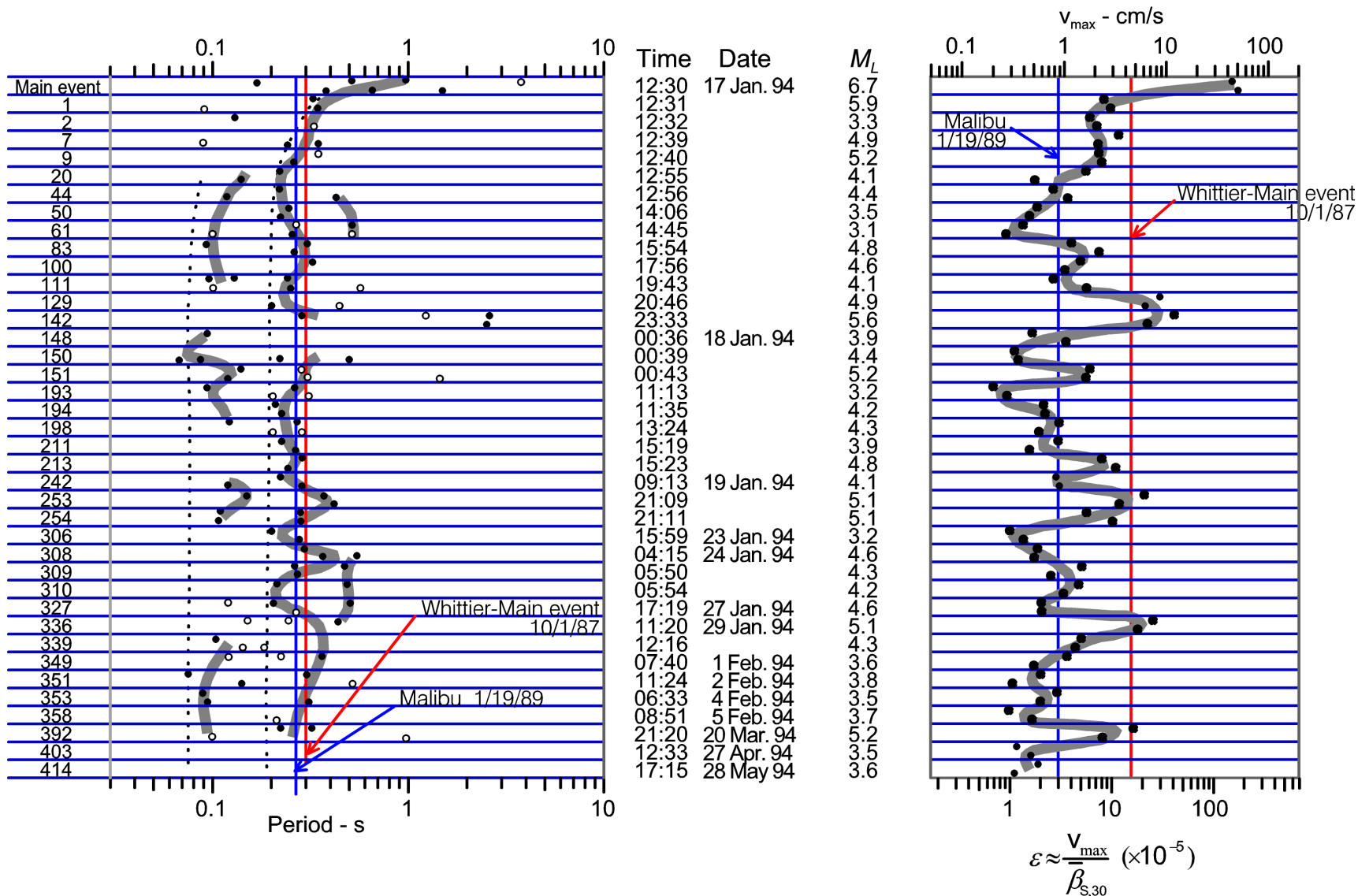
With peak ground velocity exceeding 10 cm/s, site-characteristic peaks begin to disappear, and as the peak ground velocity approaches and exceeds 100 cm/s , essentially all peaks disappear (Trifunac & Ivanović, 2003a,b). This is consistent with the conclusions of Gao et al. (1996), Hartzell (1996), and Trifunac and Todorovska (2000b) that in the near field, in the presence of nonlinear response, the measured site characteristics by small amplitude events (~linear response) cease to be valid.
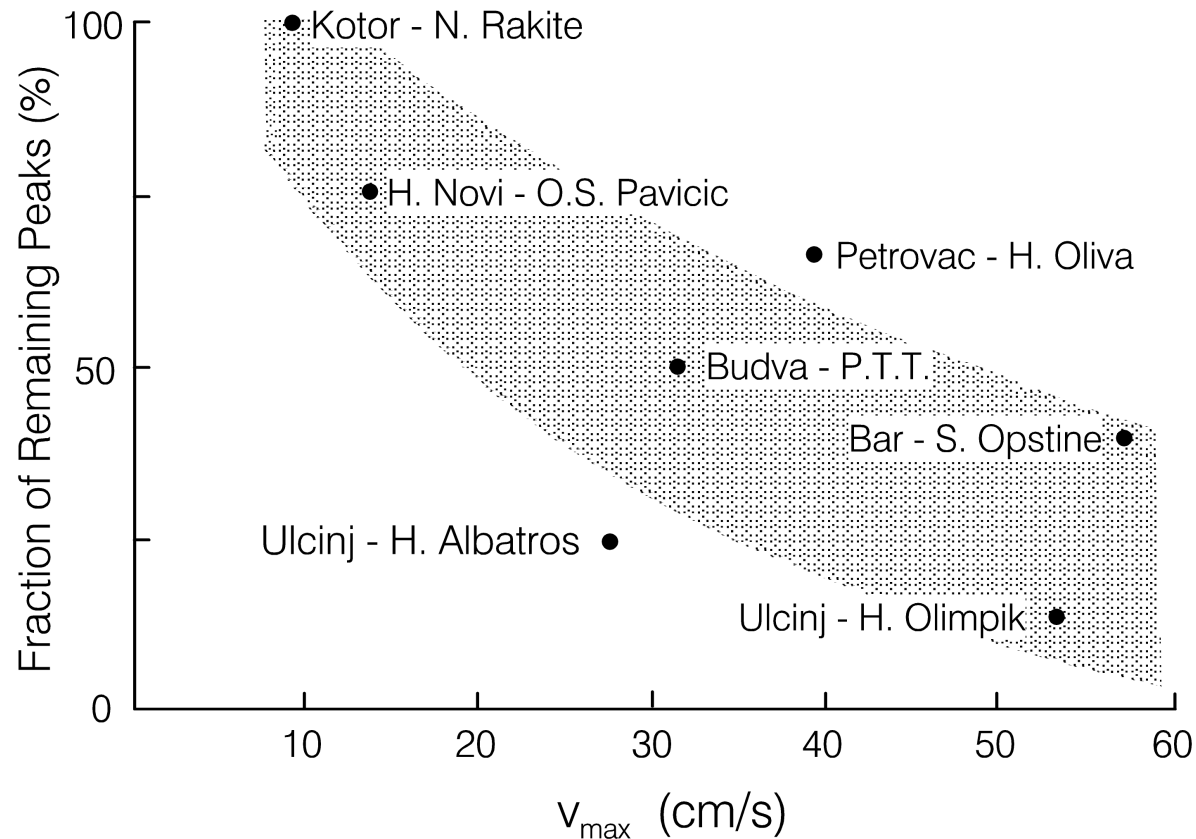
Movement of Soil Blocks. Many observations in the epicentral regions (cracks in the pavement, buckled curbs, and concentrations of breaks in the pipes of the water distribution system) show that the near-surface soil does not move as a continuum but rather as a collection of blocks of material moving 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. In their study of the repetition in the distribution patterns of damaged buildings and of broken water pipes, during San Fernando 1971 and Northridge 1994 earthquakes, Trifunac and Todorovska (2004) showed that the overall trends for both earthquakes appear to be stable, significant, and consistent. The conclusion reached is that the formation of the soil blocks (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.

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 the following figure. 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.

As can be seen from the figure bellow in the near field, for damaging levels of strong motion, local geological and soil 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 Tinsely et al. (1985), works reasonably well.
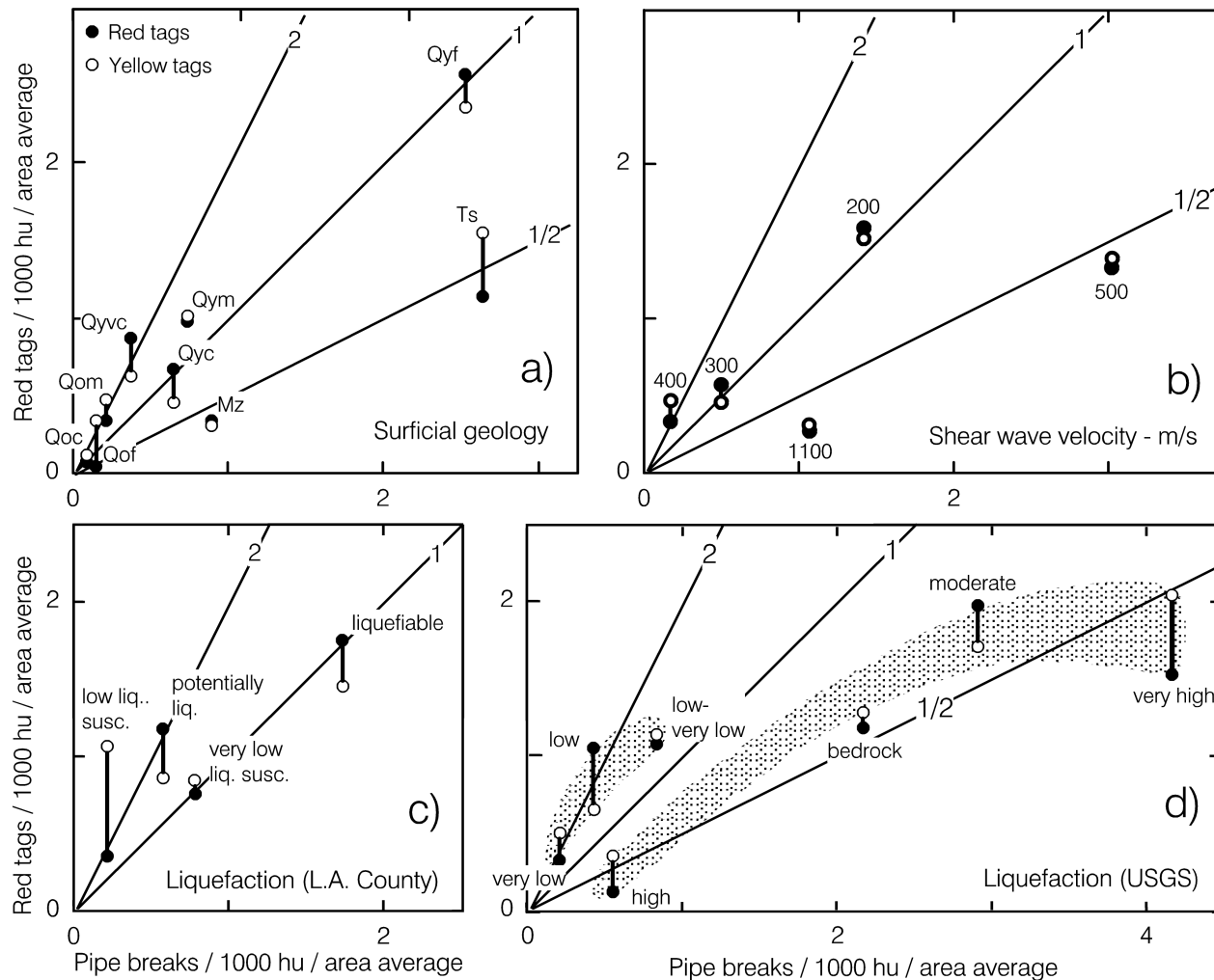
Conclusions

I have illustrated some contemporary approaches for inclusion of the effects that local site conditions have on the amplitudes of strong ground motion, and how those approaches have evolved from the linear wave-propagation theory. While this is useful in the far field, it ceases to work in the near field, where the buildings get damaged and where the soil experiences large nonlinear and permanent deformations. Refined site characterizations that correlate with the observed damage (e.g. USGS liquefaction categories) can continue to be developed, but this would still leave 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 realistically 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 velocity) 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. This can be done, but it will require coordinated and advanced research effort involving large scale nonlinear simulations and systematic analyses of past and future data on damage.