NONLINEAR SOIL RESPONSE –
1994 NORTHRIDGE, CALIFORNIA EARTHQUAKE[a]

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We thank Professor Richards for the useful and interesting discussion. We agree with his comments, but prefer to present our results as "hypothesis", to emphasize that different linear and nonlinear mechanisms contribute to the end result – reduced uncorrected peak accelerations at "soft sites".

We agree that "self-isolation" of soft sites, via nonlinear response is a "two-edged sword". However, we suggest that it should be possible, by clever design, to force the two "edges" to work one at a time, in such a way that the other "edge" is either avoided statistically (e.g. 90 percent of time) or essentially eliminated. Fortunately, in the case of the Northridge earthquake, the status quo of the overall design procedures (for wood frame structures with light roof) and the distribution of soil properties in the areas affected by the earthquake seem to have reduced a potentially larger devastation by a factor possibly equal to about two.

Figure 1 describes selected effects of the Northridge earthquake in San Fernando Valley. The gray areas show location of the heavily damaged (red-tagged) buildings (about 90% of those were single family detached – SFD dwelling, with wood frame construction). The small dots show locations of reported breaks in water pipes, and the continuous contours outline the areas where we believe that peak ground velocity, $v_{\max}$, approached or exceeded 150 cm/s (Todorovska and Trifunac 1997; Trifunac and Todorovska 1997a,b). In the central and northern parts of the valley, $v_{\max}$ exceeded

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100 cm/s, and in the southern and south western parts it was between 50 and 100 cm/s (Trifunac et. al., 1996). It is remarkable that, except where $v_{\max}$ is larger than about 150 cm/s, the areas of heavily damaged buildings and of breaks in water pipes do not overlap. We interpret this to mean that for $v_{\max}$ from around 20 cm/s up to about 150 cm/s (outside the gray areas), in typical soils of San Fernando Valley, sufficient amount of the incident seismic wave energy was dissipated by nonlinear response of the soil, so that the damage to buildings was reduced there (no red-tagged buildings). Within the gray areas and outside the closed contours, the soil probably responded more in a linear manner, thus transmitting most of the incident wave energy into the structures and damaging many of them (red-tagged buildings). In the areas within the closed contours ($v_m > 150$ cm/s), the 'second edge of the sword' began to act. The strong motion was so violent that both linear and nonlinear strains in the soil warped and distorted the building foundation so much that this contributed further to the damage caused by the inertial forces. Similar plots and observations have been presented for the Los Angeles region in Trifunac and Todorovska (1997c), and lead to the same conclusions.

The positive lesson from this disaster is that we can benefit from naturally occurring energy absorption mechanisms. The weakness of much of the current research in structural control and intelligent structures is in allowing all the seismic wave energy to enter into the foundation-structure system, and then devising complex, difficult to maintain, and expensive isolation and control devices to dissipate this energy. In contrast, it is wise to study ways of preventing this energy from entering the foundation. In this regard, the observations of the effects of the Northridge earthquake teach us where and how to begin.

The idea that soft, possibly wet layer of soil, at some depth, might absorb and redirect seismic wave energy is not new. In describing the novel concept employed in the design of the Imperial Hotel in Tokyo, Frank Lloyd Wright states: '... because of the wave movements, deep foundations like long piles would oscillate and rock the structure... That mud seemed a merciful provision – a good cushion to relieve the terrible shock. Why not float the building upon it?... '. A major problem of this original design was settlement (two feet during the 1923 Great Kanto earthquake, and total three feet and eight inches in 45 years). Along with the economic obsolescence, this settlement contributed to the decision to demolish the hotel in 1968 (Reitherman, 1980).

APPENDIX · REFERENCES

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FIGURE CAPTIONS

Fig. 1 San Fernando Valley Region. Spatial relationship of the areas which experienced heavy damage of buildings (gray zones) and the areas with large surface strain (indicated by the distribution of reported pipe breaks). The closed continuous lines outline zones where we believe the peak ground velocity was close to and exceeded 150 cm/sec.

San Fernando Valley