Verification – ProShake comparison

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Introduction

ProShake is a commercially available software product for doing one-dimensional ground response analyses. It was developed and is being maintained under the guidance of Professor Steven L. Kramer at Washington State University at Pullman, Washington, who is also the author of the book, *Geotechnical Earthquake Engineering*.

ProShake is being marketed by EduPro Civil Systems, Inc., Sammamish, WA, USA. Their website is: http://www.proshake.com

ProShake is a useful tool for checking the performance of QUAKE/W, since it is an independently developed product, and since it is based on a completely different formulation than that used in QUAKE/W. Comparison of results from these two entirely different products is a good way of validating the QUAKE/W formulation and implementation.

This example gives the results of a comparison study for three different earthquake records.

Background

ProShake is based on a frequency domain formulation. It is basically a mode superposition method. This method uses a Fast Fourier Transform (FFT) to convert the input motion from a time domain into a Fourier series frequency domain. The response at any location in the frequency domain can be obtained by using the input motion together with a transfer function. After computing the response in the frequency domain, the method uses an inverse FFT to transform the solution back to a time domain.

QUAKE/W, on the other hand, is based on a finite element formulation with a direct integration scheme in the time domain. "Direct integration" means no transformation of the equations into the frequency domain is required. Stated another way, the motion equations are solved directly using a finite-difference time-stepping procedure.

ProShake comes with an example problem that replicates the example soil profile used in the original SHAKE user's manual. SHAKE was a computer program developed at the University of California at Berkeley in the 1970's. A later version was known as SHAKE91. Today, a version with a Windows interface is available as SHAKE2000 (www.shake2000.com). ProShake uses this profile to compare the results from ProShake with SHAKE91. By having been around for so long, this soil profile has become a standard of sorts for this type of verification.

Numerical Simulation

The soil profile in SHAKE and ProShake must be defined as layers with constant properties. The layers allow for some variation in properties with depth. The SHAKE profile consists of an upper 30-foot (9 m) layer of sand. Below the sand from a depth of 30 ft down to 70 feet (21 m) is a clay layer, and under the clay is sand down to 150 feet below the ground surface. The bedrock is at the 150-foot (45 m) level. For analysis, this profile is divided into 17 layers. The upper 10 feet (3m) is divided into two 5-foot (1.5m) layers. The remaining layers are all 10 feet (3 m) in thickness. In ProShake, the bedrock is considered as a layer (#17) and is deemed to extend down a great undefined distance.

The water table is 10 feet below the ground surface (the water table actually does not come into play, since all material properties are specified as constant for each layer; that is, they are not a function of the effective overburden stress).

The ProShake problem definition can be simulated in QUAKE/W with a column of elements, as shown in Figure 1. There are 16 regions with one element per region. The base of the column is fixed. This has the effect of the earthquake motion being applied at the column base. Another way to look at this is that the bedrock is infinitely stiff and the full earthquake motion is felt at the base of the column.

The sides of the column are fixed in the vertical direction, which ensures that all the motion is in the horizontal direction only, an assumption inherent in the ProShake 1D formulation.

To make a comparison between ProShake and QUAKE/W, it is vitally important to uncheck all outcrop options in ProShake and to apply the earthquake motion at the top of the rock; that is, do not use the outcrop options in ProShake.

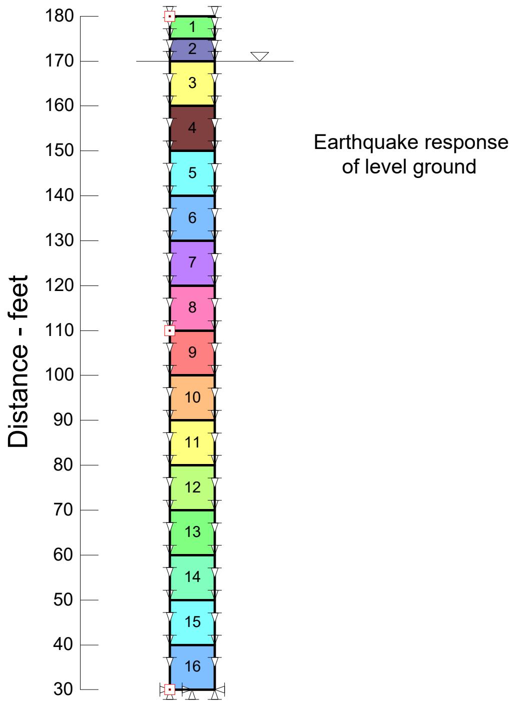

Figure 1. The SHAKE soil profile defined in QUAKE/W.

The material properties used for each of the layers are summarized in Table 1. The G reduction functions and Damping Ratio functions for the sand and clay are shown in Figure 2 and Figure 3.

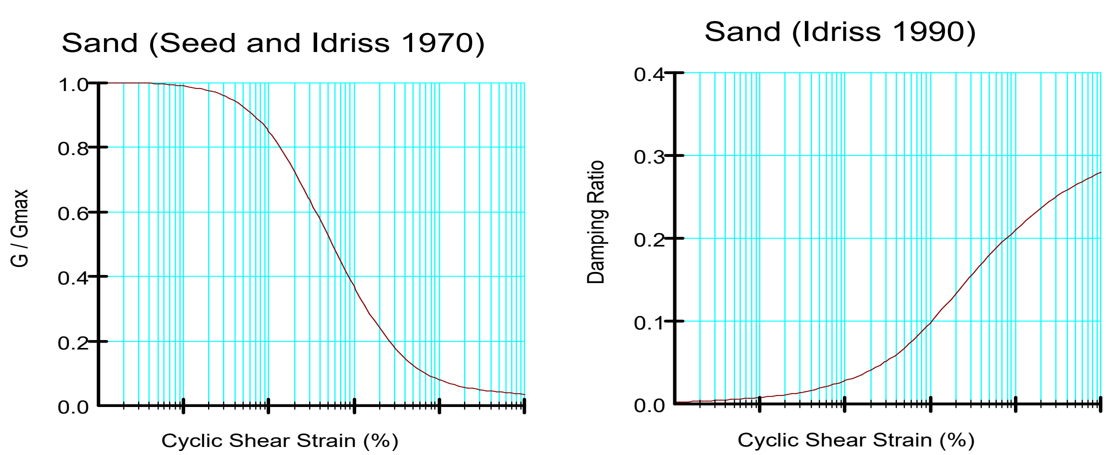

Figure 2. Property functions for the sand.

Table 1. Material properties for each layer in the QUAKE/W analysis.

Layer Number	Material Name	Thickness (m)	Unit Weight (kN/m3)	Gmax (MPa)	Vs (m/sec)	Poisson's Ratio QUAKE/W	Modulus Curve	Damping Curve
1	Sand	1.52	19.64	185.87	304.8	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
2	Sand	1.52	19.64	150.56	274.32	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
3	Sand	3.05	19.64	150.56	274.32	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
4	Sand	3.05	19.64	167.75	289.56	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
5	Clay	3.05	19.64	185.87	304.8	0.45	Clay (Seed and Sun 1989)	**Clay (Idriss 1990)**
6	Clay	3.05	19.64	185.87	304.8	0.45	Clay (Seed and Sun 1989)	**Clay (Idriss 1990)**
7	Clay	3.05	19.64	224.9	335.28	0.45	Clay (Seed and Sun 1989)	**Clay (Idriss 1990)**
8	Clay	3.05	19.64	224.9	335.28	0.45	Clay (Seed and Sun 1989)	**Clay (Idriss 1990)**
9	Sand	3.05	20.42	326.69	396.24	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
10	Sand	3.05	20.42	326.69	396.24	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
11	Sand	3.05	20.42	378.88	426.72	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
12	Sand	3.05	20.42	378.88	426.72	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
13	Sand	3.05	20.42	434.94	457.2	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
14	Sand	3.05	20.42	434.94	457.2	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
15	Sand	3.05	20.42	494.86	487.68	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
16	Sand	3.05	20.42	626.31	548.64	0.45	Sand (Seed and Idriss 1970)	**Sand (Idriss 1990)**
17	Rock	infinite	21.99	3333.49	1219.2			**0.01**

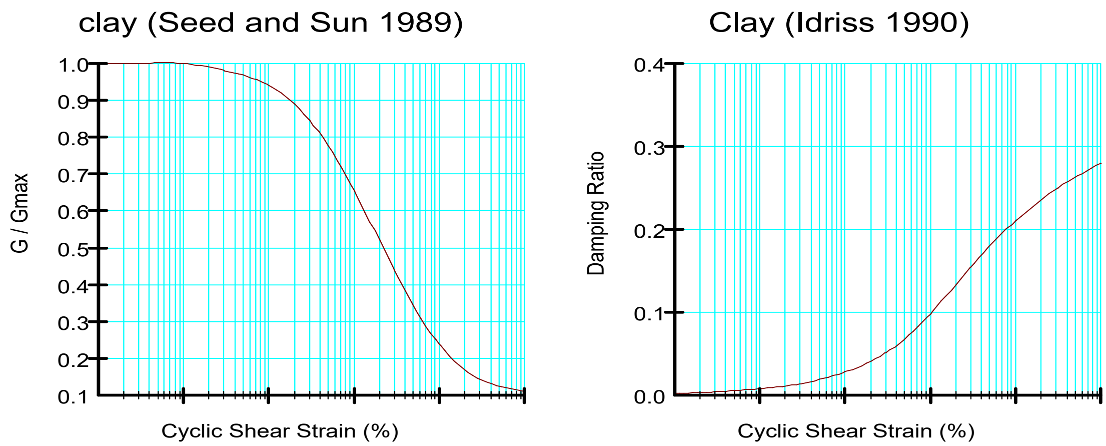

Figure 3. Property functions for the clay.

The comparisons are done here for three different earthquake time-history records. The prime motivation in selecting these records was to include records with different frequency contents. The predominant frequencies of the selected motions vary from 1.2 Hz to 12 Hz.

The records are referred to here as:

- The Treasure Island Earthquake;
- The El Centro Earthquake; and
- The Saguenay Earthquake.

The Loma Prieta Earthquake (M 6.9) occurred on October 17, 1989. The epicenter was near the Loma Prieta Peak in the Santa Cruz Mountains in California to the south-east of the San Francisco Bay area. The time-history record used here was obtained from a nearby recording station on the Treasure Island Military Base. The predominant period for this record is about 0.64 seconds (Figure 4).

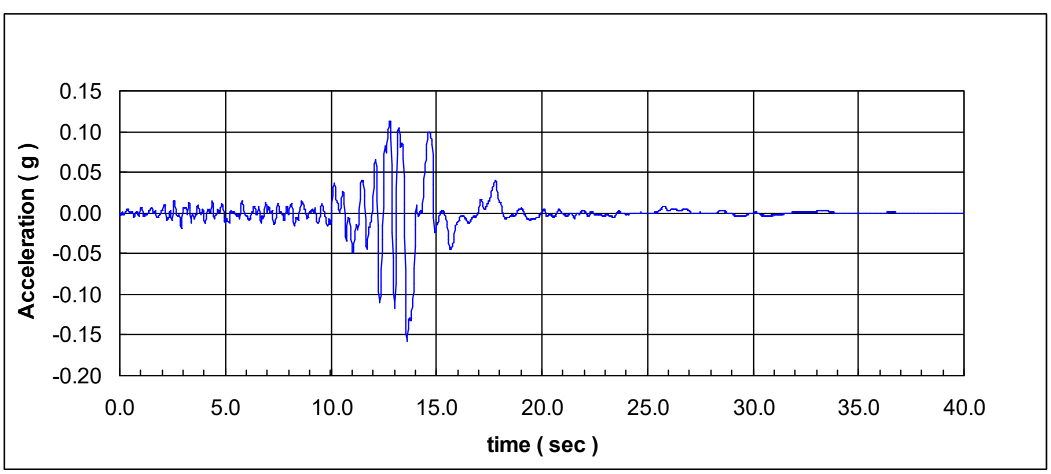

Figure 4. The Treasure Island Earthquake.

The El Centro time-history record is from the Imperial Valley Earthquake (M 7.1) that occurred in May 1940. The shock caused 40 miles of surface faulting on the Imperial Fault, which is part of the San Andreas system in southern California. The predominant period for this record is about 0.85 seconds (Figure 5).

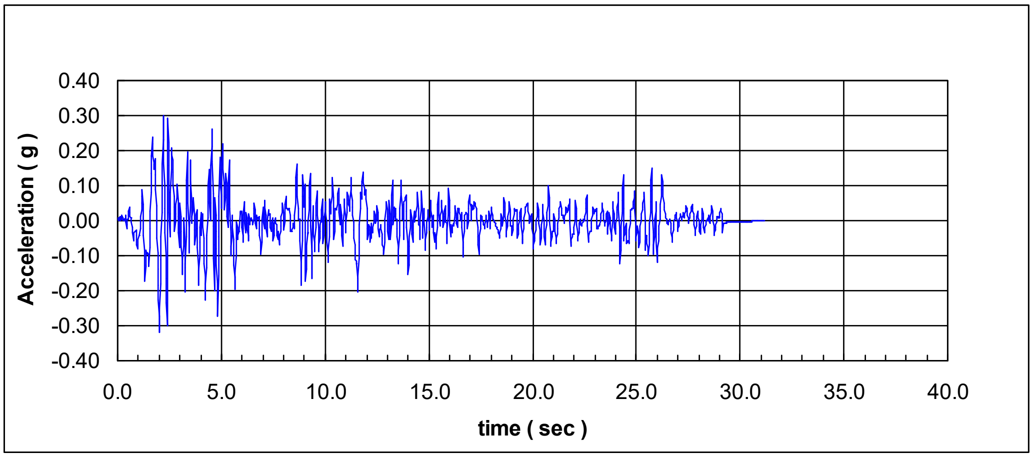

Figure 5. The El Centro Earthquake.

The Saguenay Earthquake (M 5.9) occurred in Quebec, Canada on November 25, 1988. This record is of interest because of its high frequency content. The predominant period for this record is about 0.084 seconds (Figure 6).

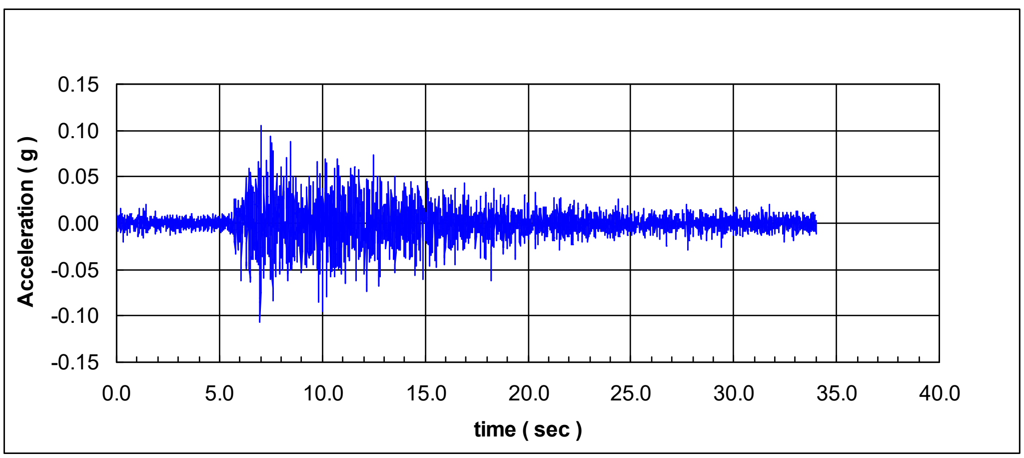

Figure 6. The Saguenay Earthquake.

The data from both QUAKE/W and ProShake were taken into EXCEL to create graphs, so that the results from both pieces of software are on the same graph.

All the graphs are self-explanatory as to the variable that is being compared.

There are two types of graphs. One group shows the variation with time at the top of the column. The other group shows the peak values on a depth profile.

Results and Discussion

Figure 7 through to Figure 19 give the QUAKE/W – ProShake comparisons for the Treasure Island Earthquake analysis.

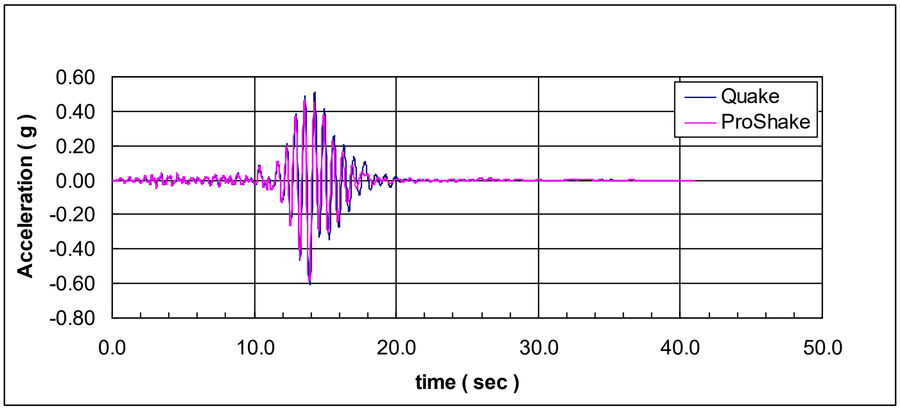

Figure 7. Treasure Island surface ground accelerations.

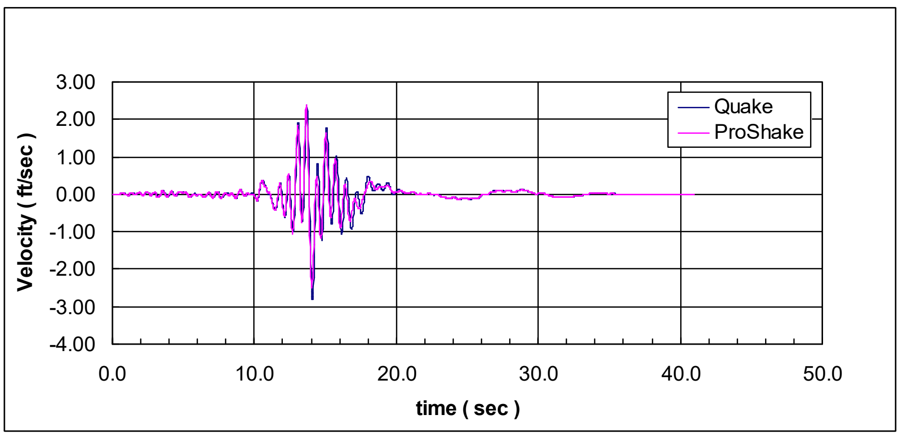

Figure 8. Treasure Island surface velocities.

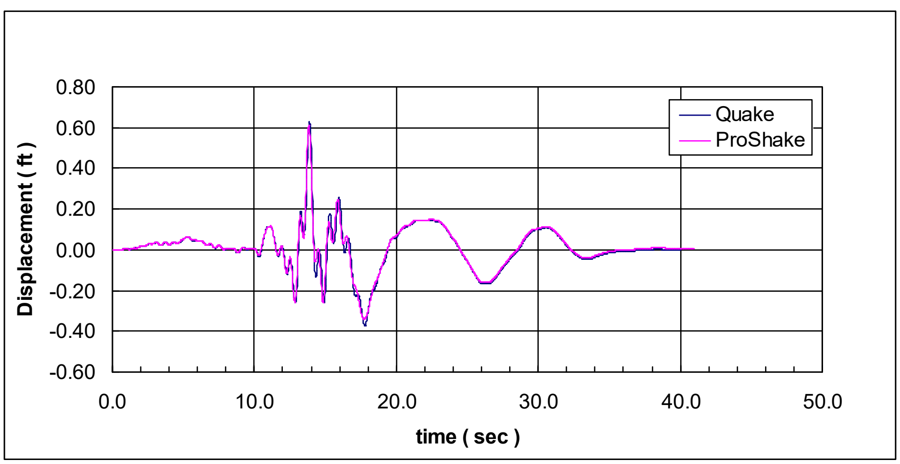

Figure 9. Treasure Island surface displacements.

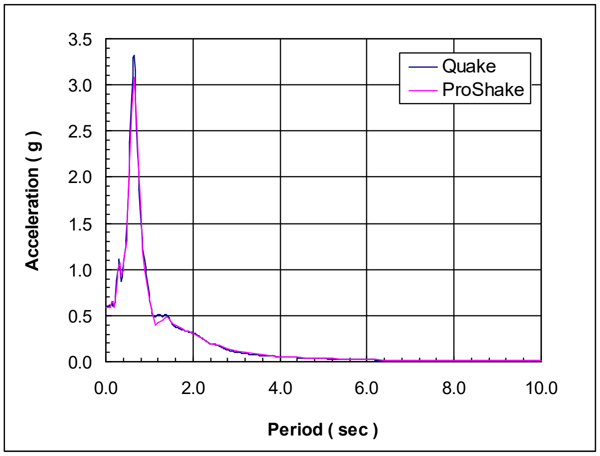

Figure 10. Treasure Island surface spectral accelerations.

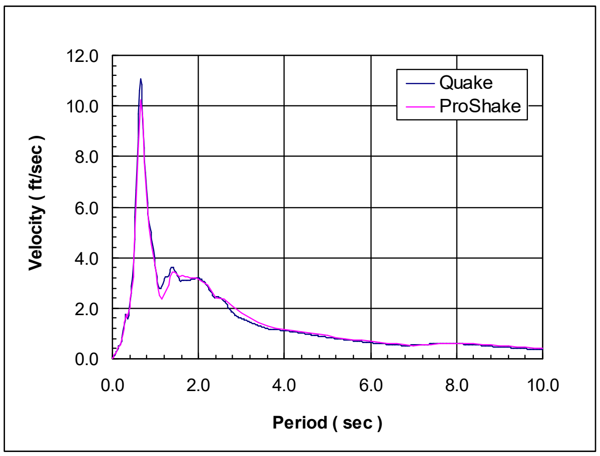

Figure 11. Treasure Island surface spectral velocities.

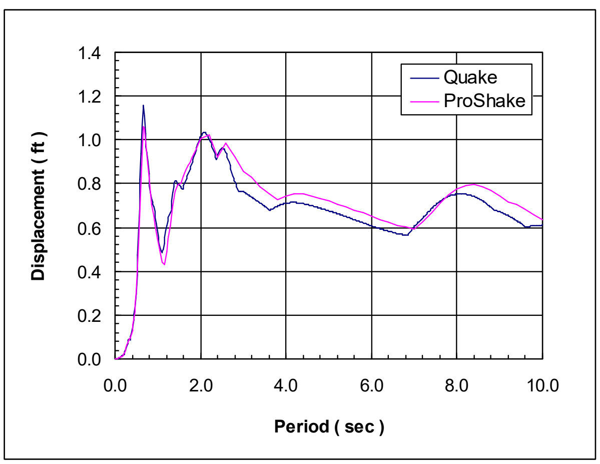

Figure 12. Treasure Island surface spectral displacements.

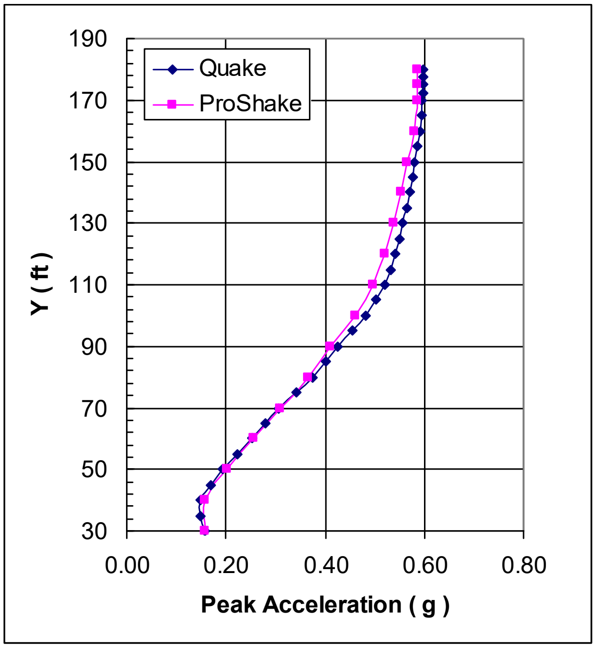

Figure 13. Treasure Island peak acceleration profile.

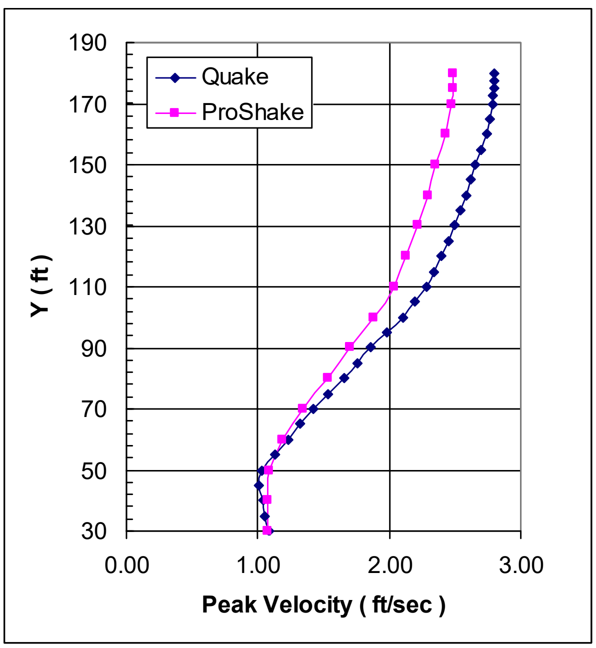

Figure 14. Treasure Island peak velocity profile.

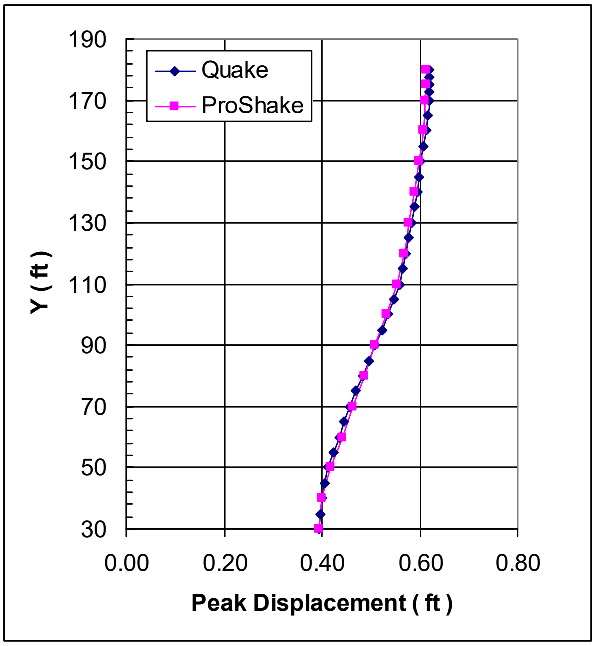

Figure 15. Treasure Island peak displacement profile.

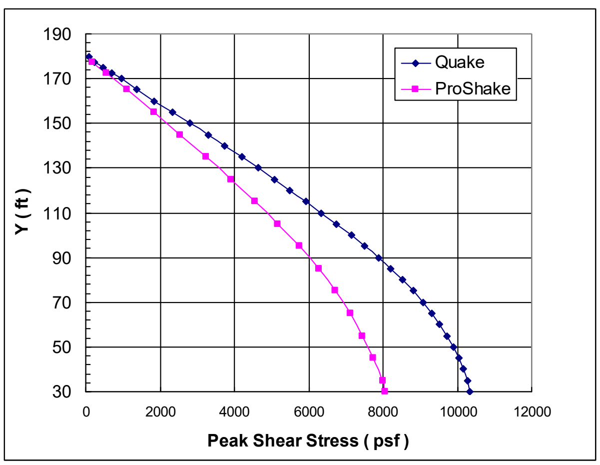

Figure 16. Treasure Island peak shear stress profile.

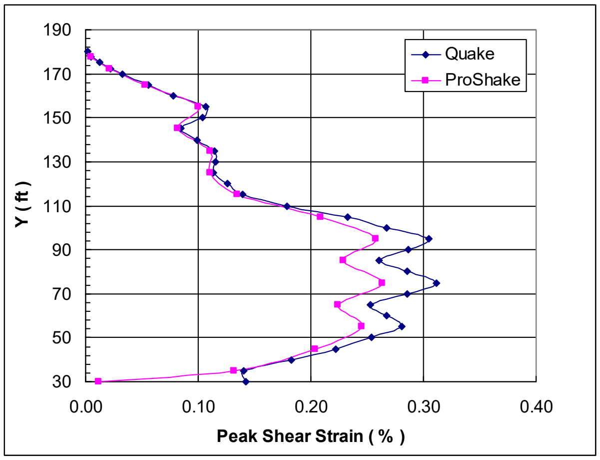

Figure 17. Treasure Island peak shear strain profile.

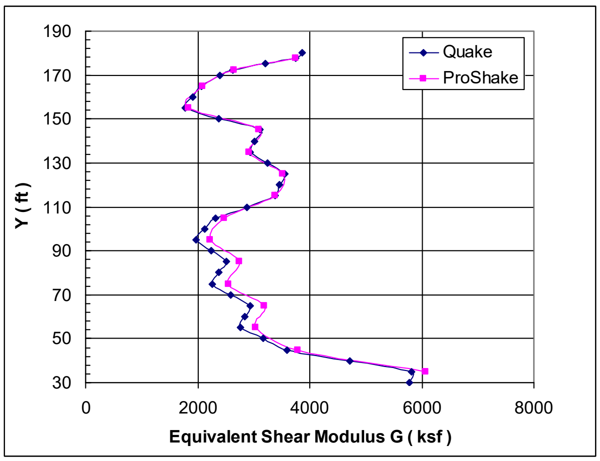

Figure 18. Treasure Island equivalent shear modulus profile.

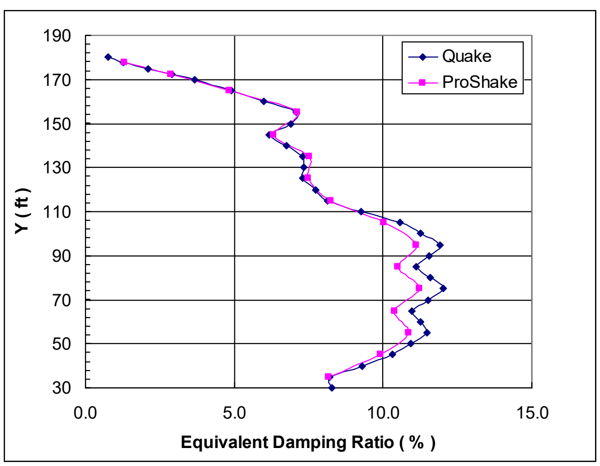

Figure 19. Treasure Island equivalent damping ratio profile.

Figure 20 through to Figure 32 give the QUAKE/W – ProShake comparisons for the El Centro earthquake analysis.

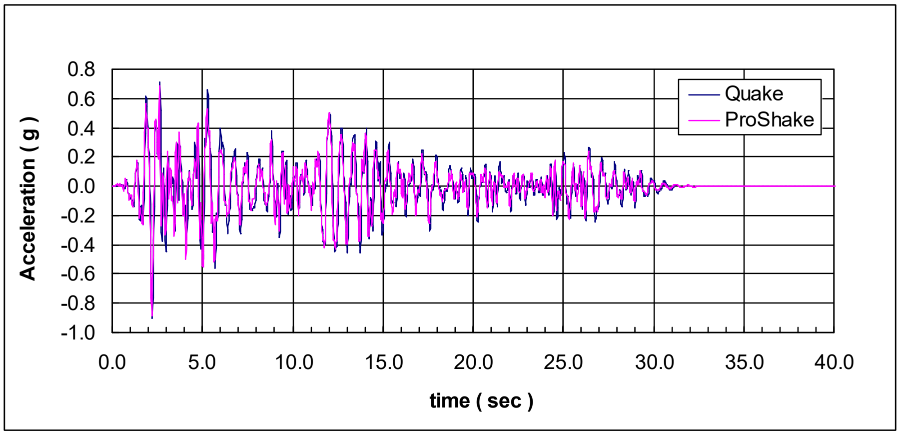

Figure 20. El Centro ground surface accelerations.

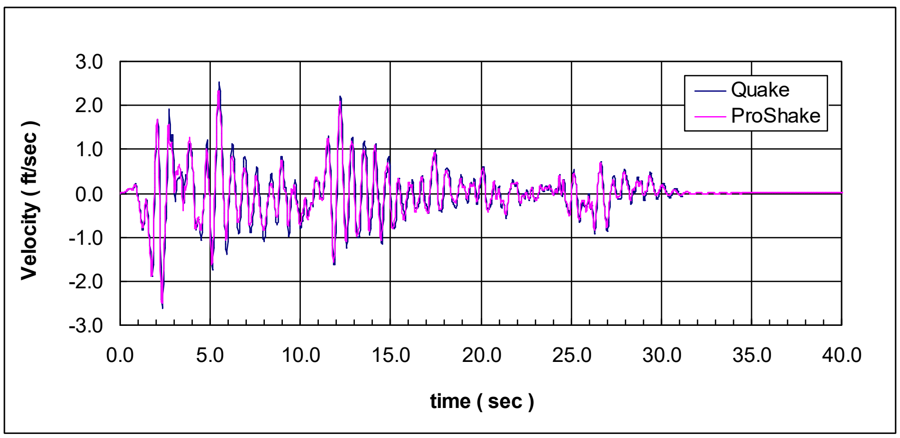

Figure 21. El Centro ground surface velocity.

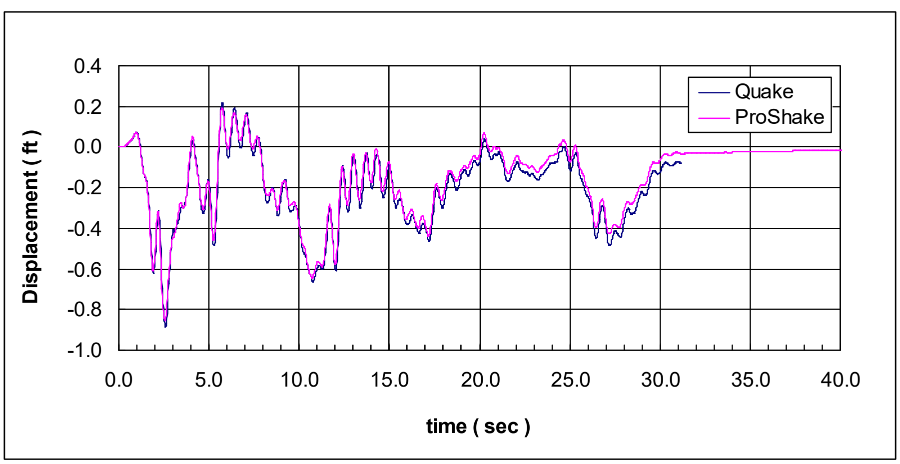

Figure 22. El Centro ground surface displacements.

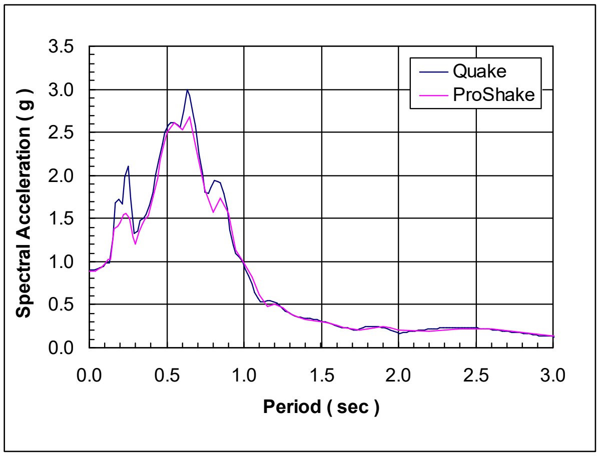

Figure 23. El Centro spectral ground surface accelerations.

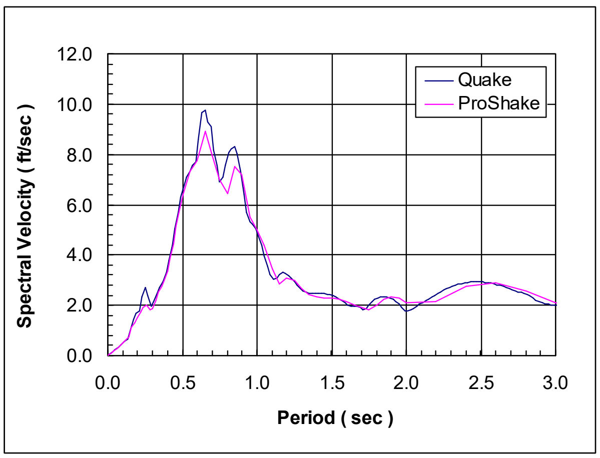

Figure 24. El Centro spectral ground surface velocity.

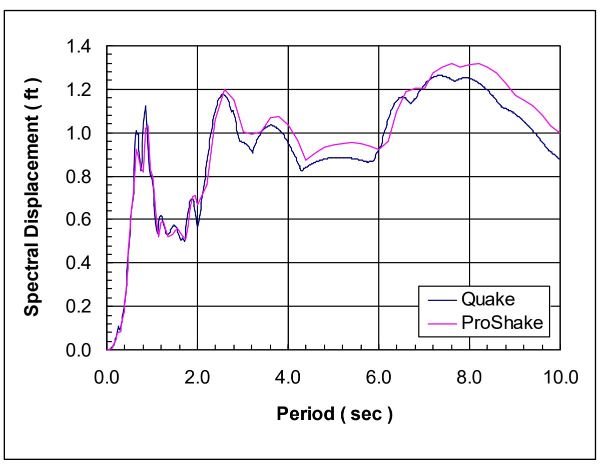

Figure 25. El Centro spectral ground surface displacement.

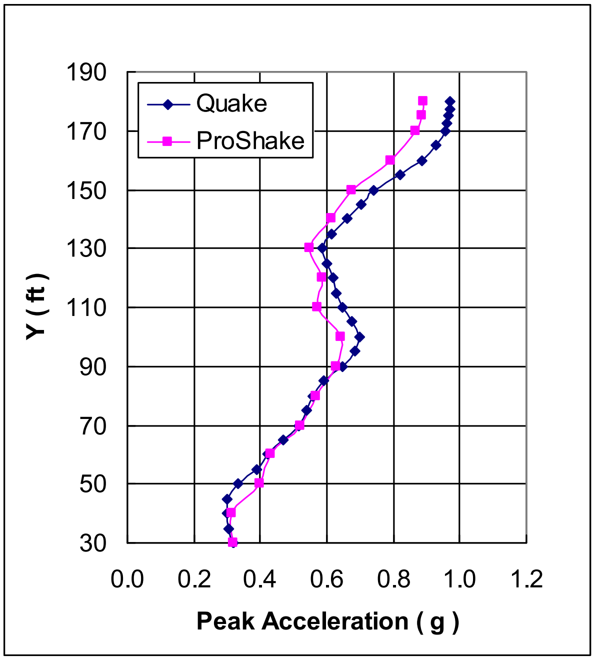

Figure 26. El Centro peak acceleration profile.

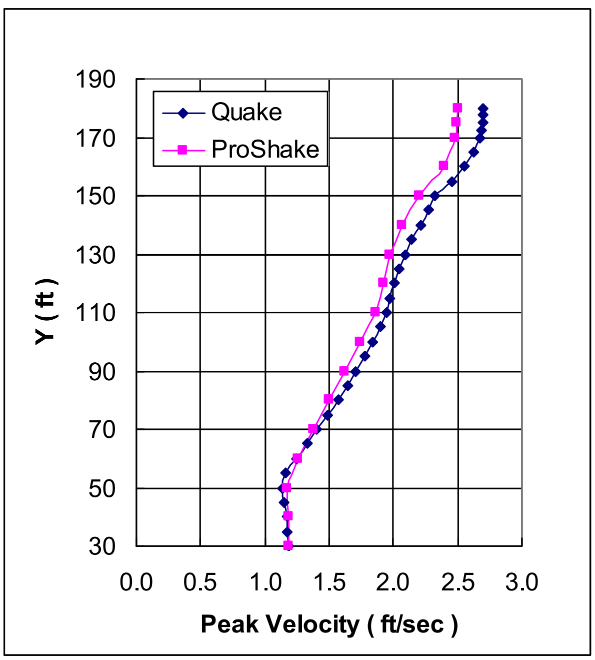

Figure 27. El Centro peak velocity profile.

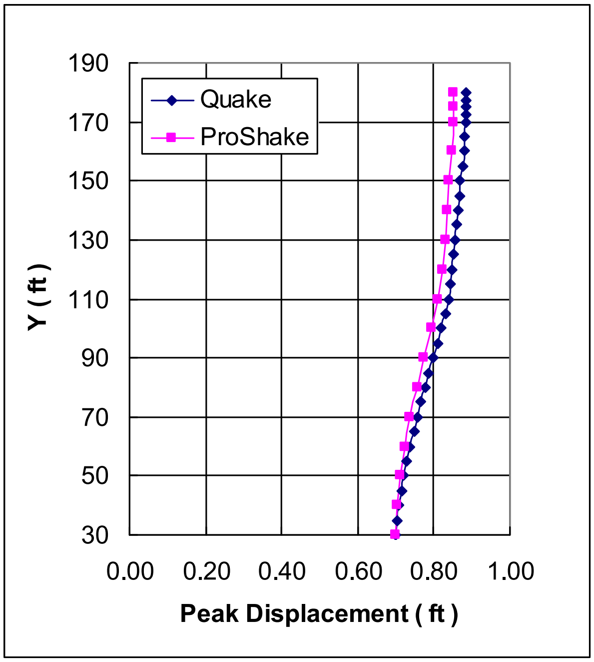

Figure 28. El Centro peak displacement profile.

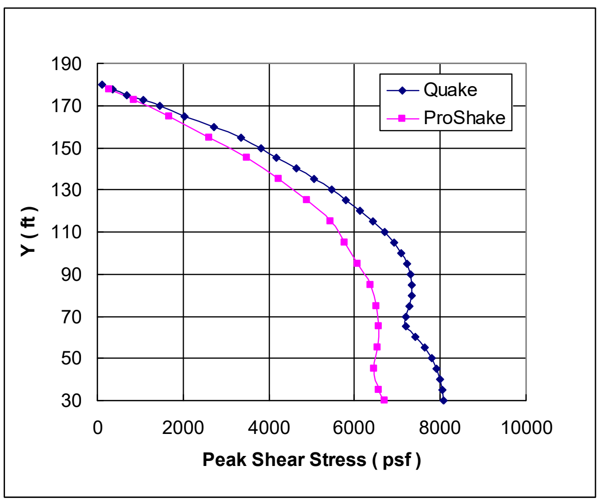

Figure 29. El Centro peak shear stress profile.

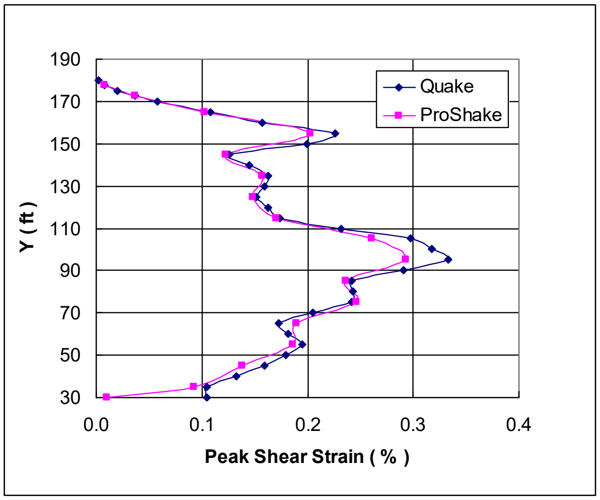

Figure 30. El Centro peak shear strain profile.

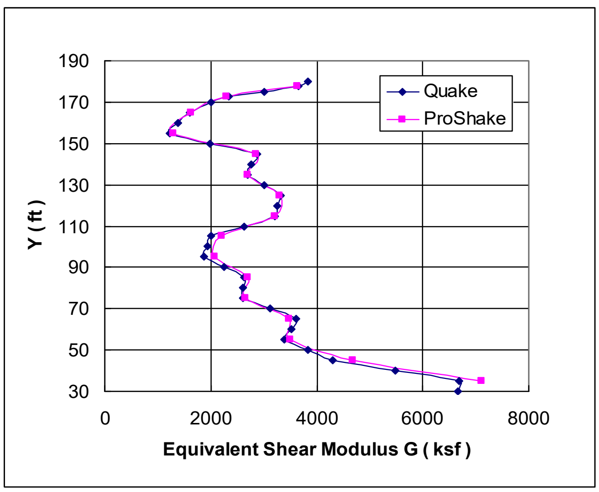

Figure 31. El Centro peak shear modulus profile.

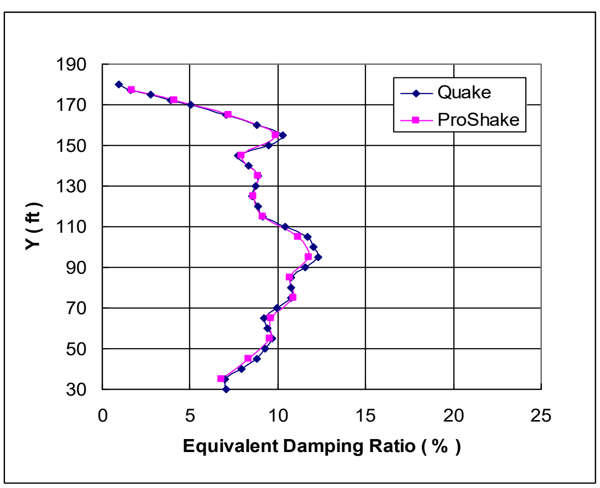

Figure 32. El Centro peak damping ratio profile.

Figure 33 through to Figure 48 give the QUAKE/W – ProShake comparisons for the Saquenay earthquake analysis.

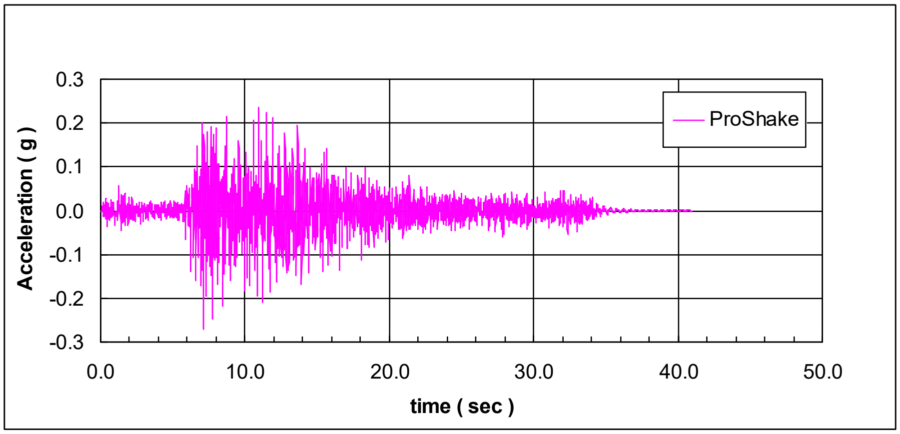

Figure 33. Saguenay ground surface acceleration.

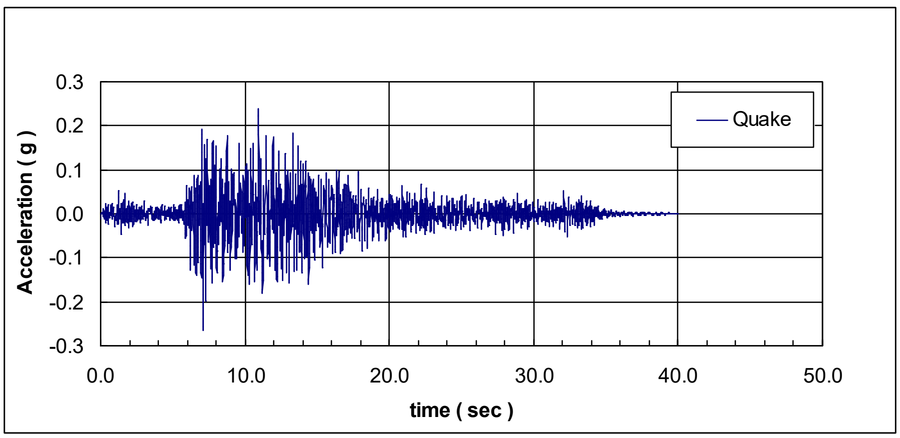

Figure 34. Saguenay ground surface acceleration.

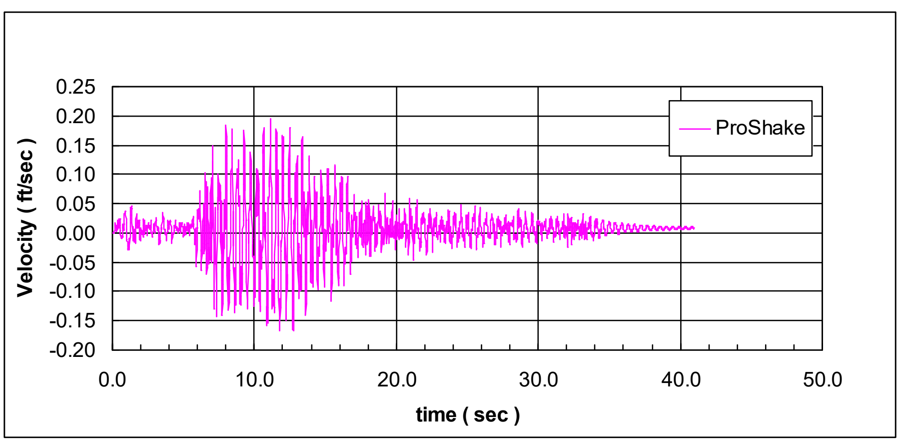

Figure 35. Saguenay ground surface velocity.

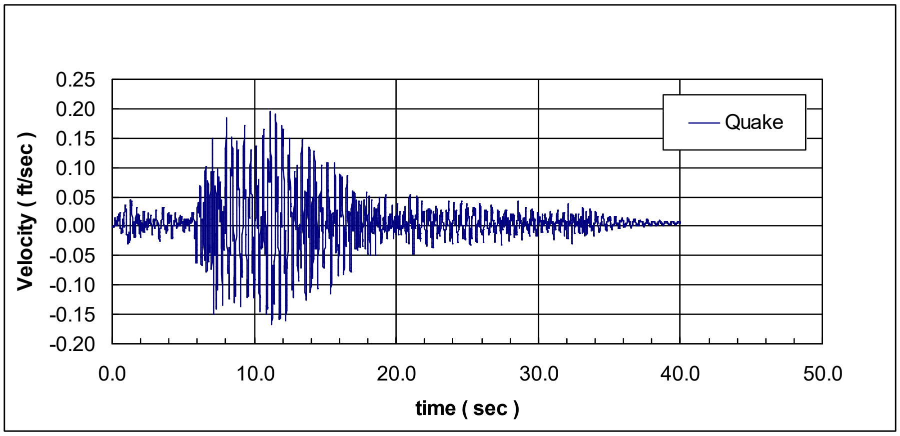

Figure 36. Saguenay ground surface velocity.

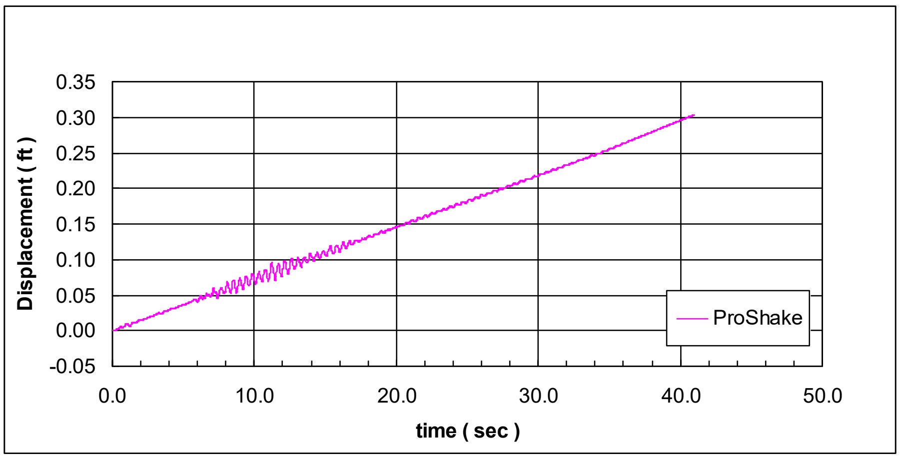

Figure 37. Saguenay ground surface displacements.

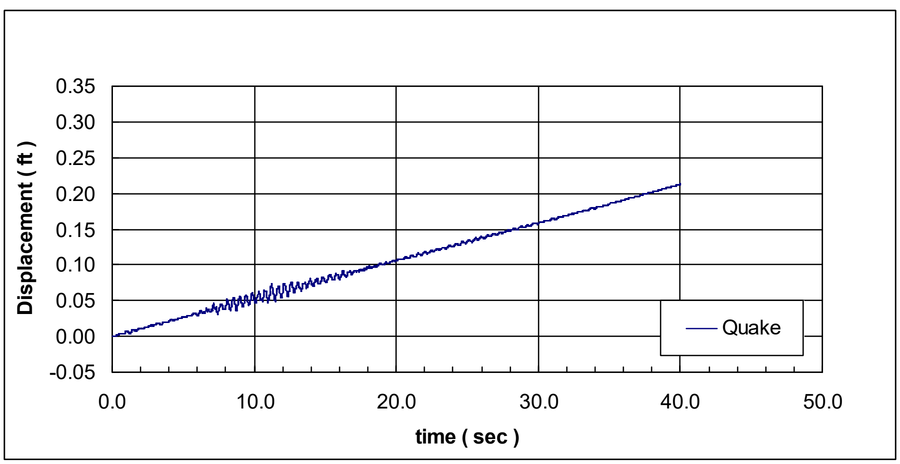

Figure 38. Saguenay ground surface displacements.

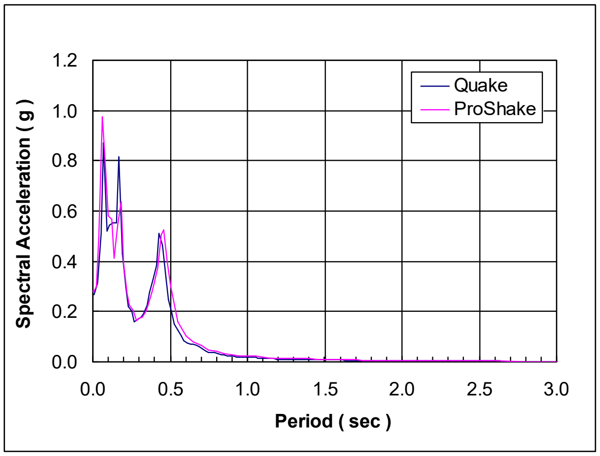

Figure 39. Saguenay spectral ground surface accelerations.

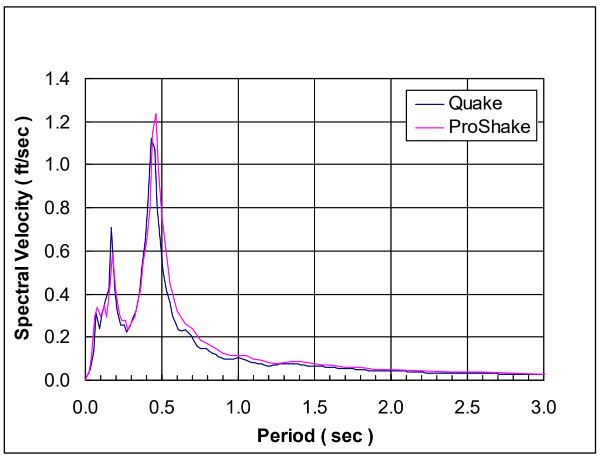

Figure 40. Saguenay spectral ground surface velocities.

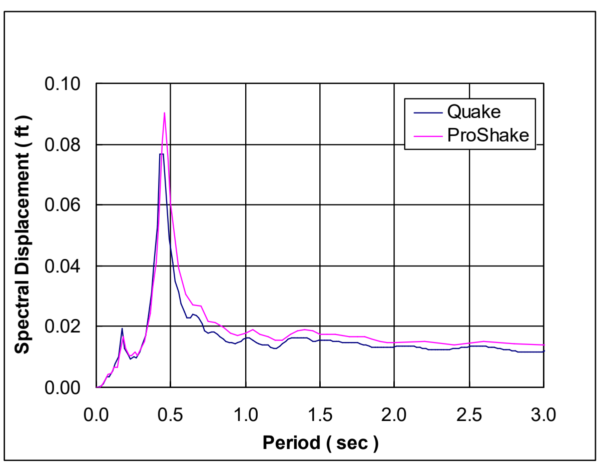

Figure 41. Saguenay spectral ground surface displacements.

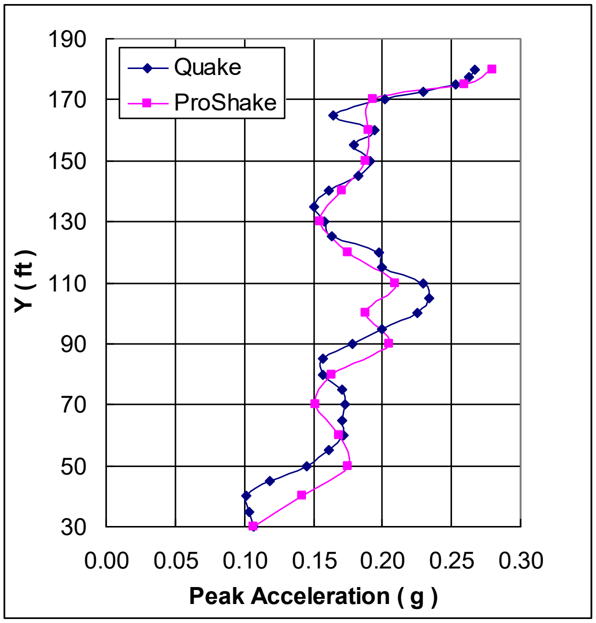

Figure 42. Saguenay peak acceleration profile.

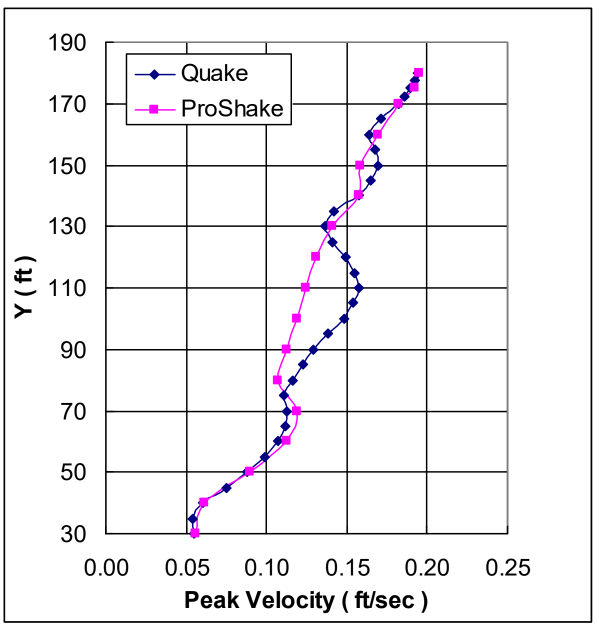

Figure 43. Saguenay peak velocity profile.

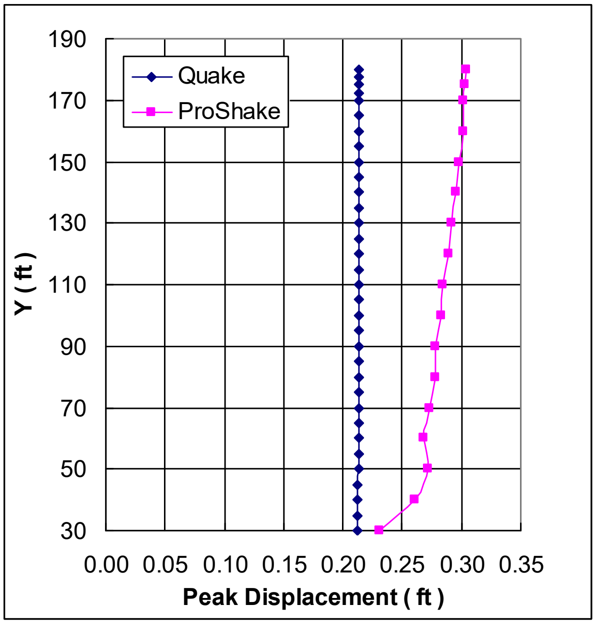

Figure 44. Saguenay peak displacement profile.

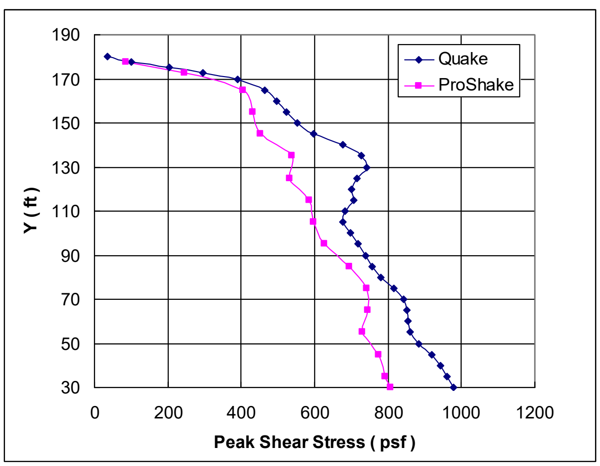

Figure 45. Saguenay peak shear stress profile.

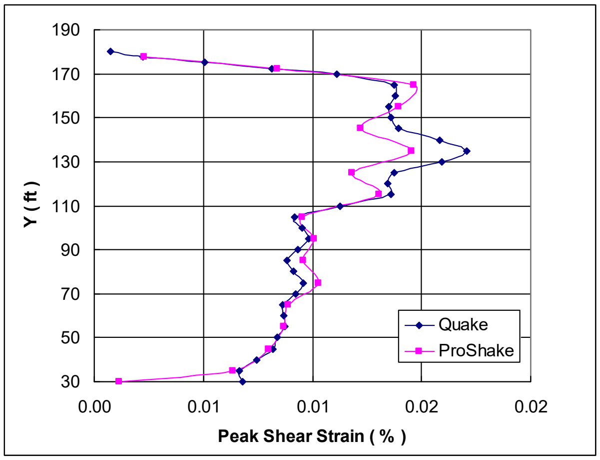

Figure 46. Saguenay peak shear strain profile.

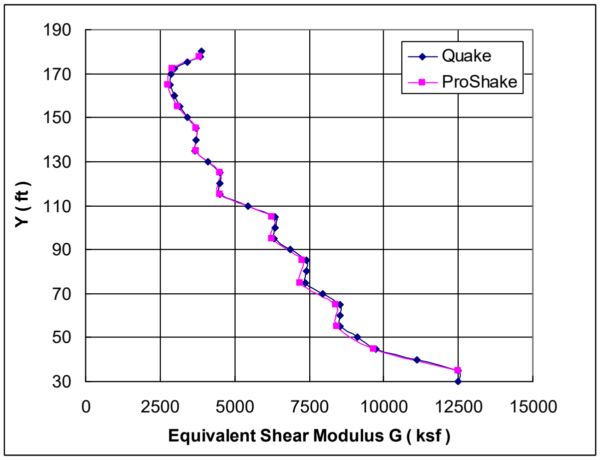

Figure 47. Saguenay equivalent shear modulus profile.

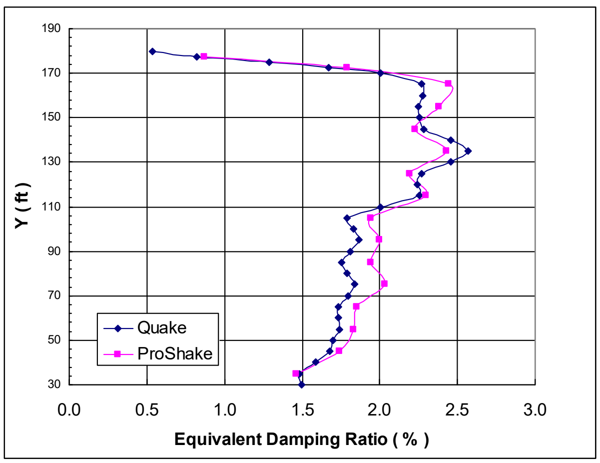

Figure 48. Saguenay equivalent damping ratio profile.

Summary and Conclusions

The agreement between the QUAKE/W and ProShake results is remarkably close, especially when considering the vastly different theories and formulations on which the two products are based.

The one exception where there is some noticeable difference is in the shear stress profile. This is understandable. In QUAKE/W, the base is fixed, and so very slight changes in the motion could cause significant changes in the shear stress. In ProShake, the base is not fixed, and so is slightly more flexible, which could cause the shear stress to be different. When considering that the boundary conditions are so entirely different, it is surprising that the shear stress profiles are as close as they actually are.

The close agreement in the comparisons lends credence to the conclusion that both products are formulated and implemented in accordance with the theory.

Where there are differences, it is not possible to say which product is more correct.

In the end, the comparative study here provides strong evidence that the QUAKE/W formulation and implementation is correct.