SEEQUENT

GeoStudio Example File
Level Ground Shaking

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Introduction

The main objective of this example is to illustrate how QUAKE/W can be used to do a one-dimensional ground response analysis. Often these types of analyses are done with software products that are specifically designed for this purpose. One such product is ProShake (see the QUAKE/W – ProShake Comparison Example for more details). QUAKE/W, however, can be used equally well for this type of analysis. Moreover, a true effective stress nonlinear analysis can be done with QUAKE/W, which is not available in a frequency domain formulation, such as ProShake.

This example includes both an Equivalent Linear-type of analysis and an effective stress Nonlinear-type of analysis.

Numerical Simulation

The problem consists of analyzing a 20 m stratum of sand (Figure 1). The sand sits on rock and the water table is 2 m below the ground surface. The material properties used for these analyses are somewhat arbitrary. The form and shape of the property functions are realistic, but the magnitudes have been selected to illustrate the features and capabilities of QUAKE/W.

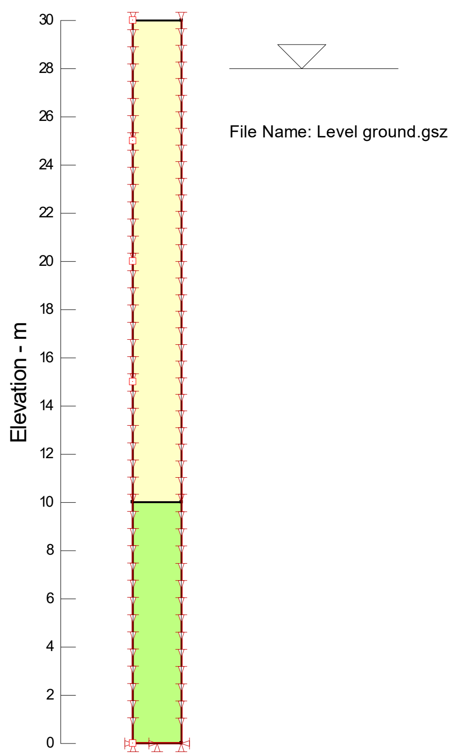

Figure 1. Problem configuration.

The first step is to establish the *in situ* stress and pore-water pressure conditions that exist prior to the earthquake shaking. This is completed by creating an Initial Static analysis as the Parent to the subsequent analyses. The initial pore-water pressure conditions are defined using a water table drawn at an elevation of 28 m.

The total unit weight and Poisson's ratio (v) are required for this part of the analysis. The specified soil stiffness properties are not used to compute the *in situ* stresses. The at rest earth pressure coefficient (K_o) is controlled indirectly through v. Recall that:

$$\sigma_h = \sigma_v K_o$$ **Equation 1**

$$K_o = \frac{v}{1 - v}$$ **Equation 1**

In a one-dimensional analysis for level ground, it is often best to make the horizontal ground stresses (σ_h) equal to the vertical stresses (σ_v). By doing this, the vertical effective stress approaches zero when the horizontal effective stress approaches zero, a situation where the ground, in essence, becomes liquefied. In this way, liquefaction occurs when the pore-water pressure becomes equal to the overburden.

Making v equal to 0.5 is equivalent to a K_o of 1.0. For numerical reasons, the maximum value allowed in QUAKE/W is 0.495, which results in the horizontal stress not being exactly equal to the vertical stress, but it is close enough for all practical considerations.

The earthquake time history record used for the two child analyses is shown in Figure 2. The record was scaled in QUAKE/W so that the maximum is 0.2 g and the length is 14 seconds. The data points are at an even interval of 0.01 (1/100th) of a second.

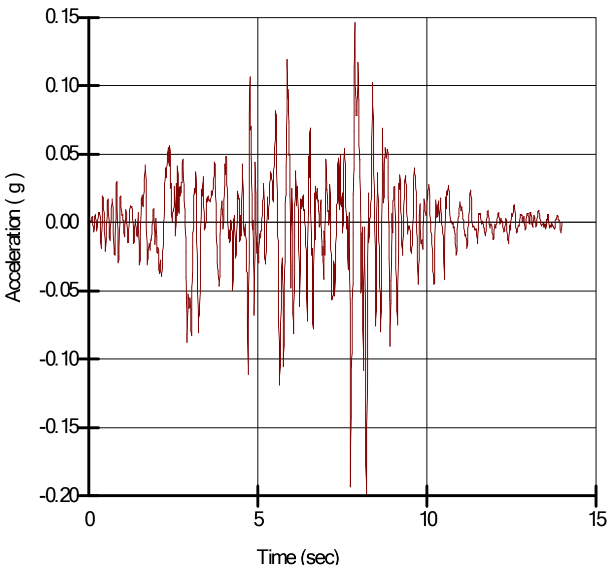

Figure 2. Earthquake time history record.

The first dynamic analysis is done using the Equivalent Linear method. Fundamentally, with this method, the soil properties are kept constant for a run though the entire earthquake record. The peak or maximum shear strains are kept track of for each element (or for each Gauss point within the element). The shear Modulus *G* and Damping Ratio are then modified based on the peak shear strains. Then, another pass is made through the entire earthquake record with the modified stiffness and damping properties. This is repeated for a specified number of passes though the earthquake record (set at 5 for this example).

The sand stiffness modulus G_{max} varies with overburden (effective vertical stress), as in Figure 3. The minimum value is 5000 kPa and the maximum value is 126,920 kPa. G_{max} for the underlying rock is treated as a constant 500,000 kPa.

The G modulus is reduced in response to the shear stains that develop, as in Figure 4.

The damping ratio function is presented by Figure 5. The same function is used for the sand and for the rock.

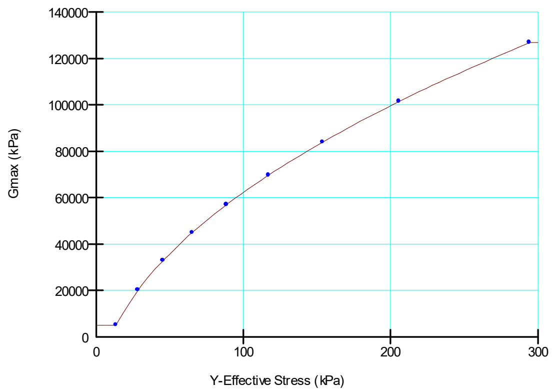

Figure 3. G_{max} function.

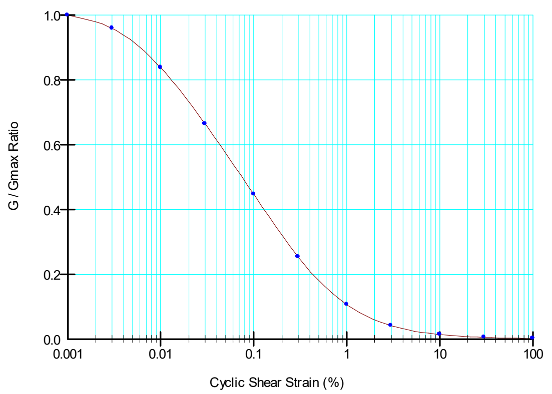

Figure 4. The G reduction curve for the sand.

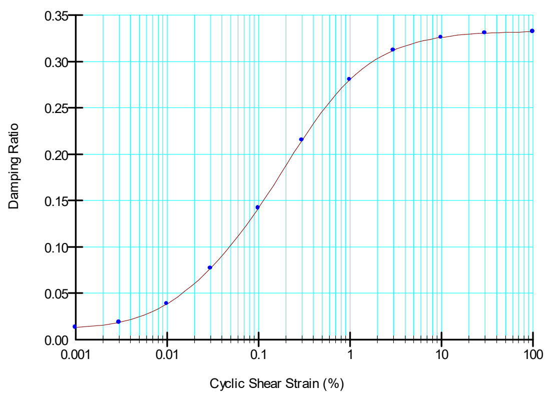

Figure 5. Damping ratio function.

A key piece of data required for estimating the development of excess pore-water pressures is the Cyclic Number function. The sample function for medium loose sand, included with QUAKE/W, is used for this analysis (Figure 6).

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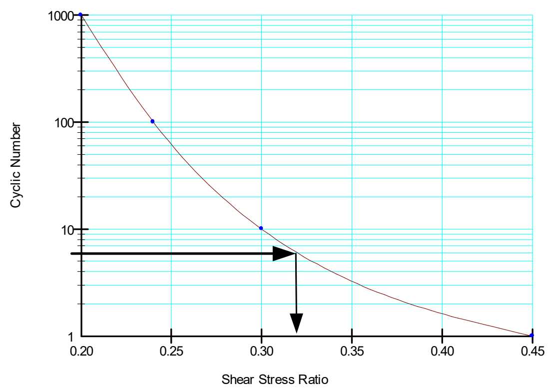

Figure 6. The cyclic number function.

The earthquake is assumed to be of a magnitude that produces six (6) equivalent uniform cycles. This is a user-specified value. It is useful to think of this as the actual number of uniform cycles the ground will experience. The horizontal line in Figure 6 represents the six equivalent uniform earthquake cycles.

In Figure 6, the six cycles correspond to a cyclic shear stress ratio (CSR) of about 0.32. This means that for this particular earthquake, together with this specified function, peak CSR's greater than 0.32 will lead to liquefaction and peak CSR's less than about 0.32 will not lead to liquefaction. We will see this in the results later.

Other material properties can be viewed in the related GeoStudio data file.

The analysis is now repeated, but with the Non-Linear type of analysis.

In a Non-linear analysis, the developing excess pore-water pressures are computed as part of each Δt time integration step. That is, excess pore-water pressures are computed as the analysis proceeds through the earthquake record, as opposed to at the end of the dynamic analysis in the Equivalent Linear method. Since the developing excess pore-water pressures are known during the temporal integration, the material properties can be adjusted in accordance with the corresponding effective stress changes. This is why it is referred to as an effective stress analysis.

The G_{max} function (Figure 3) defined for the Equivalent Linear analysis above can also be used for the Non-Linear analysis.

For the Non-Linear method, it is necessary to specify the effective strength parameters c' and ϕ', which in this example are zero and 34 degrees.

The Non-Linear method in QUAKE/W uses the MFS (Martin Finn Seed) pore-water pressure model. To use this pore-water pressure model, it is necessary to specify the functions in Figure 7 and Figure 8.

Figure 7 gives the volumetric strain that could occur for a given number of stress cycles at particular testing shear strain amplitude. For the analysis here, the testing shear strain amplitude is specified as 0.28% (the value was arbitrarily chosen for this analysis simply to illustrate features and procedures).

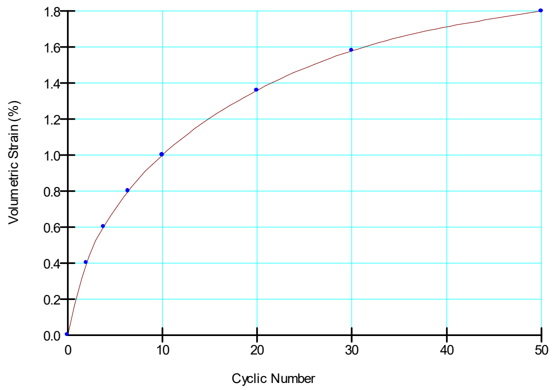

Figure 7. Volumetric strain versus stress cycles.

The sample E_r function included with QUAKE/W is used here and modified such that the minimum value is 20,000 kPa. This adjustment is also arbitrary for this illustrative analysis.

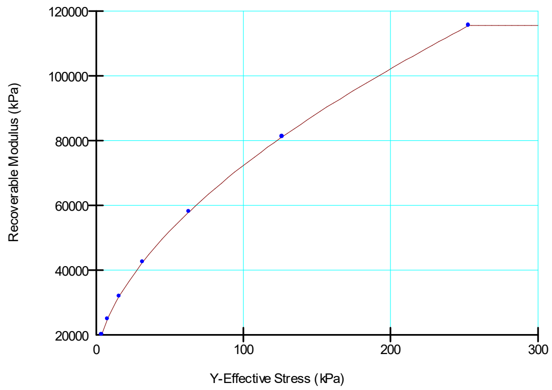

Figure 8. Recoverable modulus function.

Results and Discussion

Figure 9 shows a profile of the vertical and horizontal effective stresses resulting from the Initial Static analysis. The horizontal stress on the left is just slightly less than the vertical stress curve on the right, which is due to ν not being exactly 0.5.

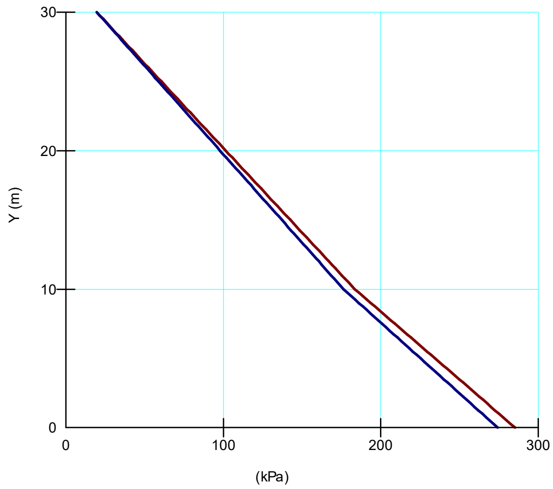

Figure 9. Vertical and horizontal (Y and X) effective *in situ* stresses.

A History Point can be placed at the base of the problem, where the specified displacement is zero; that is, the problem is fixed. Looking at the acceleration with time at the fixed base gives a graph that replicates the input earthquake record.

The response at the ground surface in the Equivalent Linear analysis is presented in Figure 10. Figure 11 compares the ground surface response with the input record (base history point). This figure shows that there is some magnification at the ground surface.

Such comparisons can be made at other History Points, if that is deemed to be of interest.

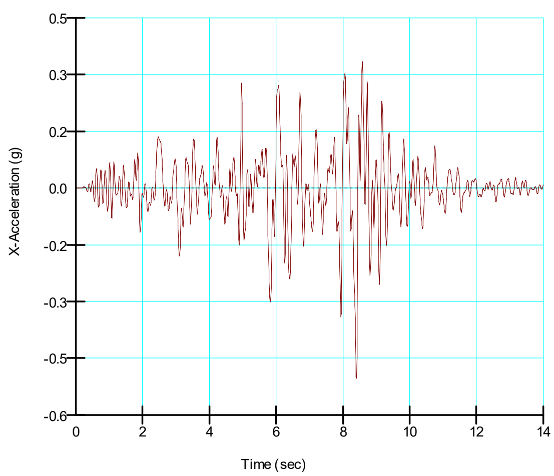

Figure 10. Ground response at the ground surface.

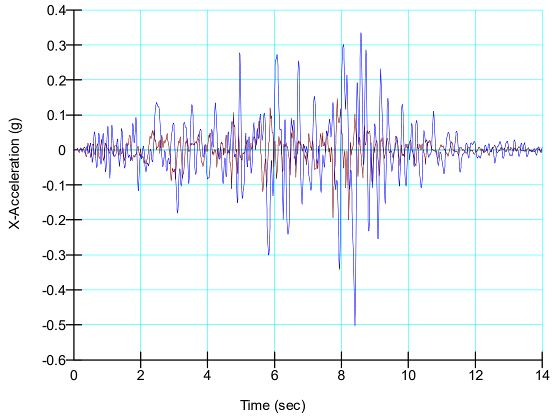

Figure 11. Replication of earthquake record at the fixed base.

The lateral movement of the ground is illustrated by the displacement profiles in Figure 12. The movement relative to the fixed base is shown on the left. The actual movements are on the right, which includes the base movement plus the relative movements.

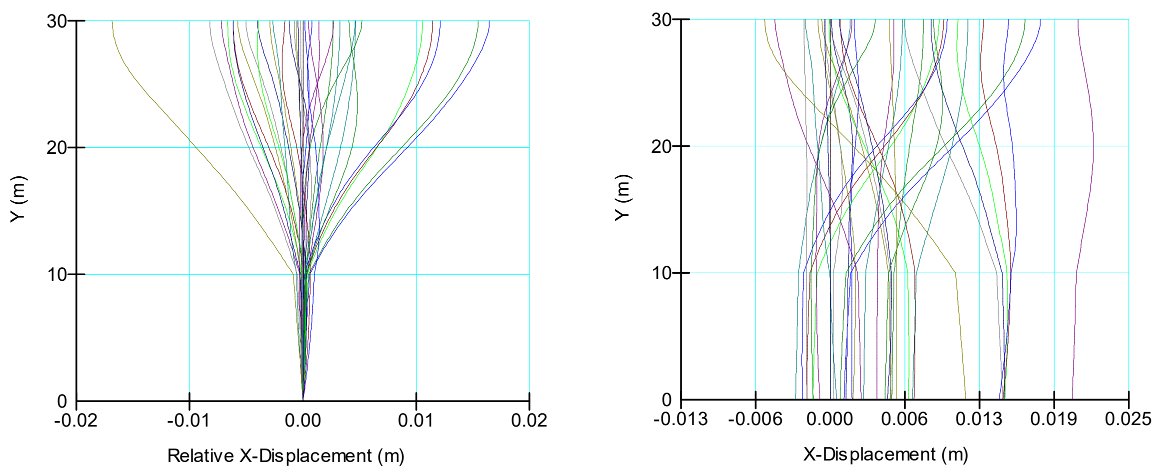

Figure 12. Lateral movement profiles.

It is very important to be mindful of the fact that in a dynamic analysis like this, it is only relative movements that create dynamic shear stresses, which in turn lead to excess pore-water pressures.

The resulting peak CSR profile is shown in Figure 13. Recall from the discussion above that liquefaction will be initiated where the CSR is greater than about 0.32. This means that a good portion of the sand has liquefied, since a large portion of the profile is above this value. This is confirmed by the shaded zone in Figure 14, which marks the zone of liquefaction.

This is further illustrated by the effective stress profiles in Figure 15. The effective stress has essentially diminished to zero, which is the definition of liquefaction.

The related excess pore-water pressure profile is shown in Figure 16.

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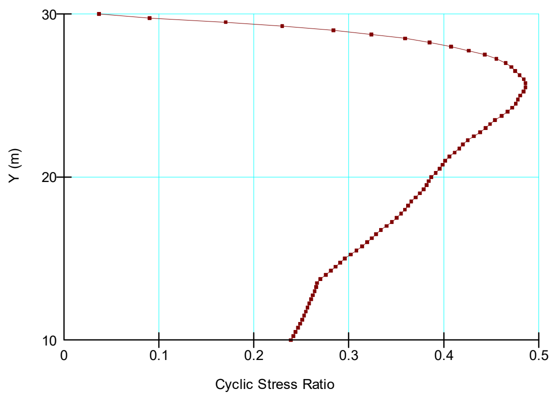

Figure 13. Peak CSR profile.

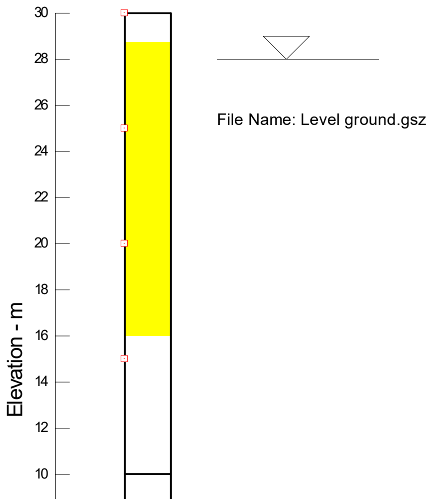

Figure 14. Zone of liquefaction.

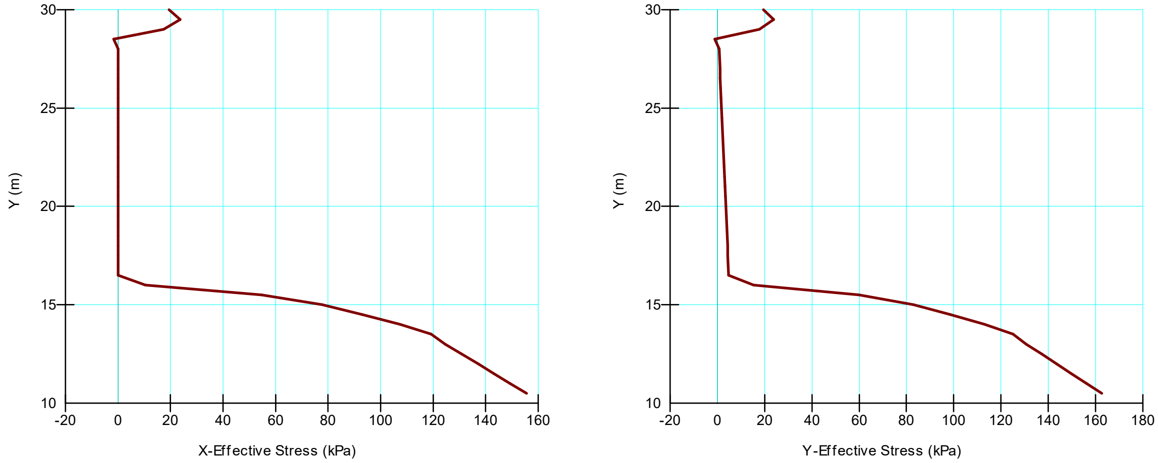

Figure 15. Effective stress profiles.

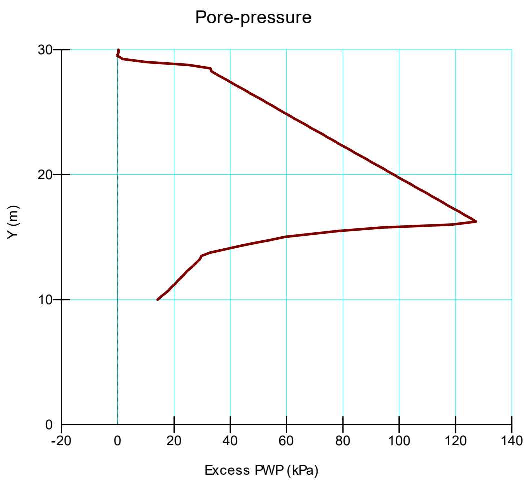

Figure 16. Excess pore-water pressure in the sand.

Figure 17 shows the acceleration versus time response at the ground surface in the Non-Linear analysis. It is quite similar to the response from the E.L. analysis discussed earlier. The peaks are slightly higher, but overall the response records are similar.

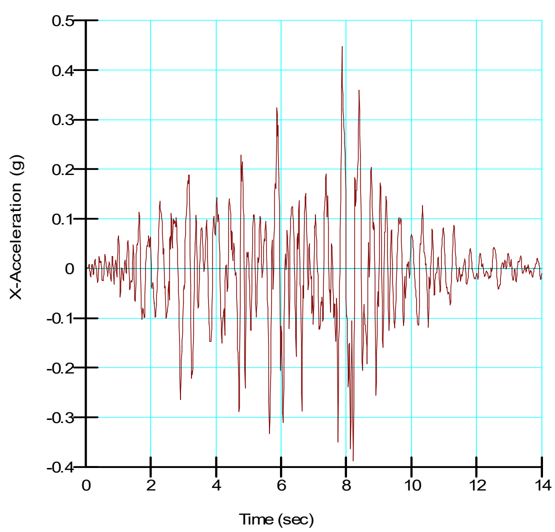

Figure 17. Ground response at the ground surface from the Non-Linear analysis.

The relative lateral movements are illustrated in Figure 18.

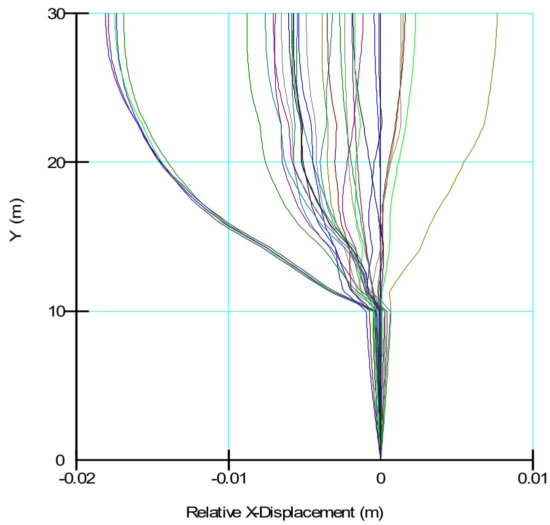

Figure 18. Relative lateral movement profiles from the Non-Linear analysis.

Figure 19 shows the nature of the stress-strain paths that occur during a Non-Linear analysis. The non-linearity is evident in the curvature of some of the paths, as is the tendency toward a hyperbolic shape that is inherent in the formulation.

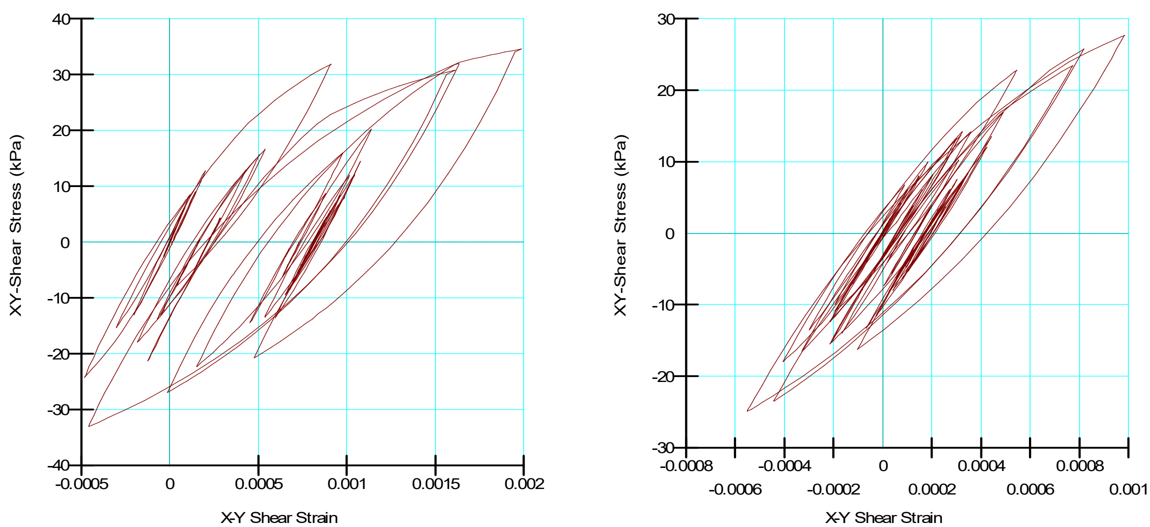

Figure 19. Stress-strain paths at Elevation 15 and 20 metres.

Figure 20 shows the resulting zone of liquefaction and Figure 21 shows the final horizontal effective stress profile. Note how the effective stress is zero in the zone of liquefaction.

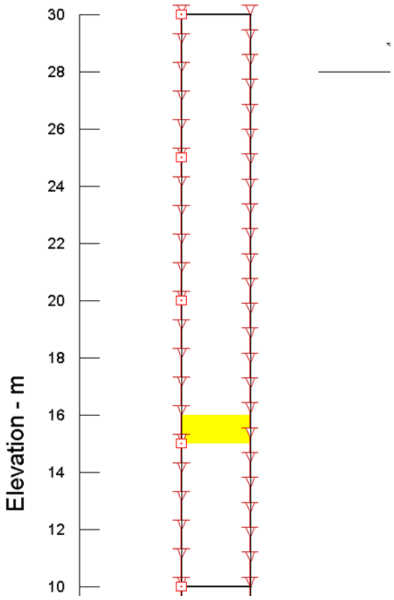

Figure 20. Liquefaction zone.

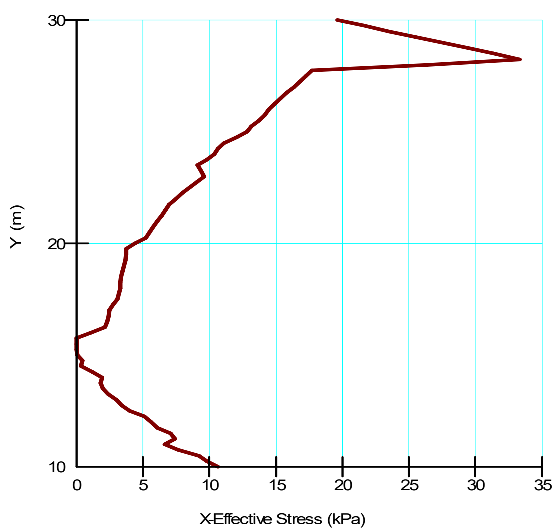

Figure 21. Horizontal effective stress profile.

Figure 22 illustrates how the excess pore-water pressure developed in the liquefied zone during the shaking. Note how the pore-water pressure increase stopped when the effective stress reached zero. This is an arbitrary cutoff in QUAKE/W in an attempt to control the numerical stability of the solution.

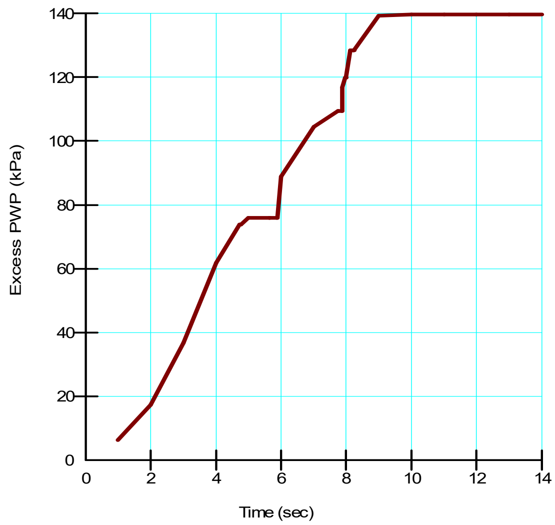

Figure 22. Development of excess pore-water pressure with time during the shaking.

Summary and Conclusions

There are many other graphs and plots that can be conveniently created to interrogate and study the analysis results. The ones shown here are only a sample of what can be done with QUAKE/W.

Both the Equivalent Linear and effective stress Non-Linear methods have been used here with differing results, especially with respect to the generation of excess pore-water pressures. These are two vastly different formulations, and when only using approximated material properties, there is very little reason to expect that the results will be nearly similar. A much more careful comparison would be required to make comments on which method better represents actual field conditions.

This example illustrates that QUAKE/W can used very effectively to do a one-dimensional ground response analysis; an exercise common in many site evaluation projects.