Level Ground Response Analysis

1 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 design for this purpose. One such product is ProShake (see the QUAKE/W – ProShake Comparison Example for more details). QUAKE/W can however 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.

2 Configuration and setup

The problem consists of analyzing a 20-metre stratum of sand, as illustrated in Figure 1. The sand sits on rock and the watertable is 2 m below the ground surface.

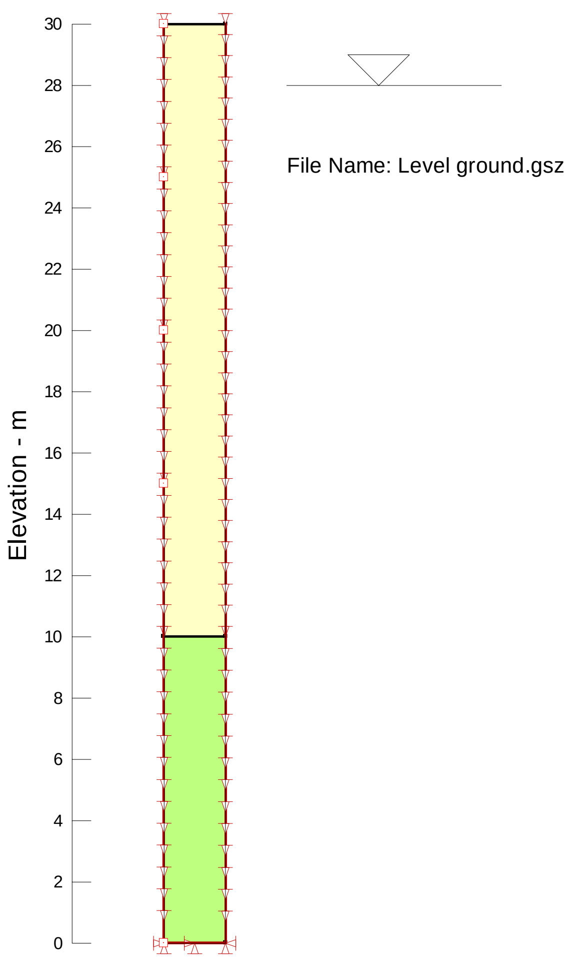

Figure 1 Problem configuration

3 Material properties

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.

4 Initial insitu conditions

The first step is to establish the insitu stress and pore-pressure conditions that exist prior to the earthquake shaking.

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 insitu stresses. The at rest earth pressure coefficient K_o is controlled indirectly through v. Recall that,

$$\sigma_h = \sigma_v \, K_o$$

$$K_o = \frac{\nu}{1-\nu}$$

In a one-dimensional analysis like this for level ground, it is often best to make the horizontal ground stresses equal to the vertical stresses. 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-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.

Figure 2 shows a profile of the vertical and horizontal effective stresses. The horizontal stress on the left is just slightly less than the vertical stress curve on the right, which is due to v not being exactly 0.5.

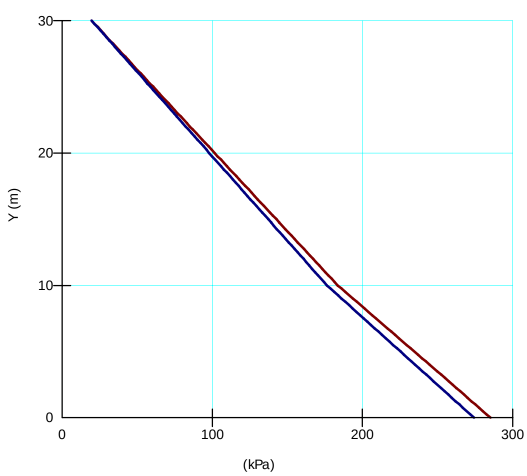

Figure 2 Vertical and horizontal (Y and X) effective insitu stresses

5 Earthquake record

The earthquake time history record used for these analyses is shown in Figure 3. The record was scaled in QUAKE/W so that the maximum is 0.2 g and a length of 14 seconds. The data points are at an even interval of 0.01 (1/100th) of a second.

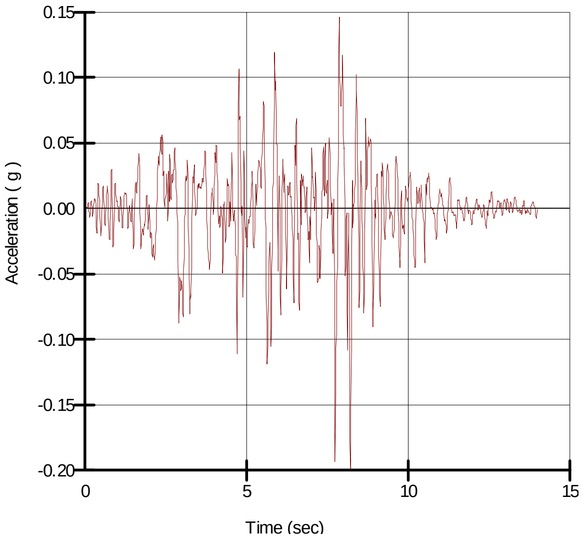

Figure 3 Earthquake time history record

6 Equivalent linear analysis

The 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 until the final results from two passes through the record are within a specified tolerance.

6.1 Material properties

The sand stiffness modulus G_{max} varies with overburden (effective vertical stress), as in Figure 4. 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 5.

The damping ratio function is presented by Figure 6. The same function is used for the sand and for the rock.

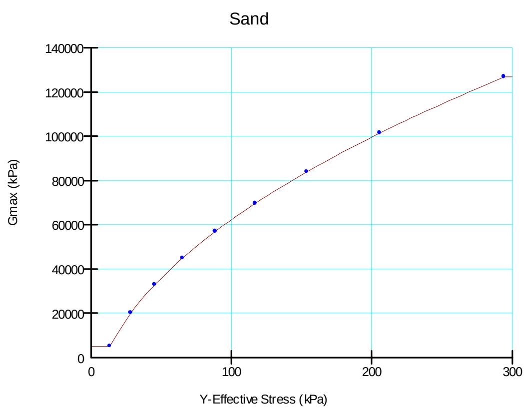

Figure 4 G_{max} function

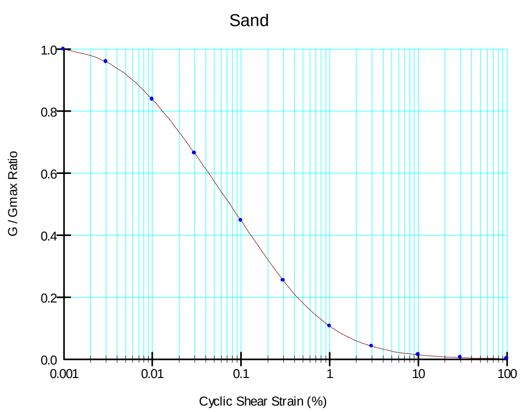

Figure 5 The G reduction curve for the sand

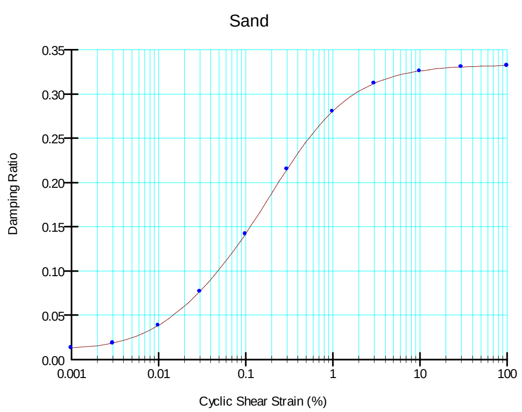

Figure 6 Damping ratio function

A key piece of data required for estimating the development of excess pore-pressures is the Cyclic Number function. The sample function for medium loose sand, included with QUAKE/W, is used for this analysis. The function is presented in Figure 7.

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 7 represents the six equivalent uniform earthquake cycles.

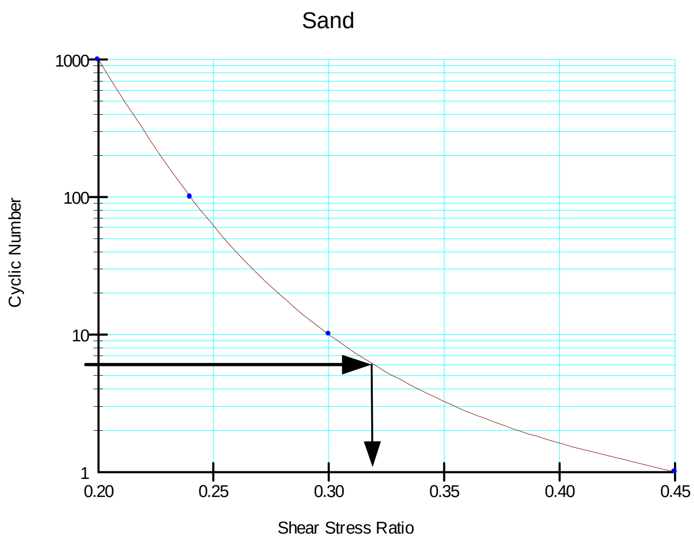

Figure 7 The cyclic number function

In Figure 7, 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.

6.2 Response to the earthquake shaking

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 can be compared with the input earthquake record by examining Figure 8 and Figure 9 . There is some magnification at the ground surface, but it is not all that dramatic. The peak at the ground surface is just over 0.3 g while the peak at the base is 0.2 g.

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

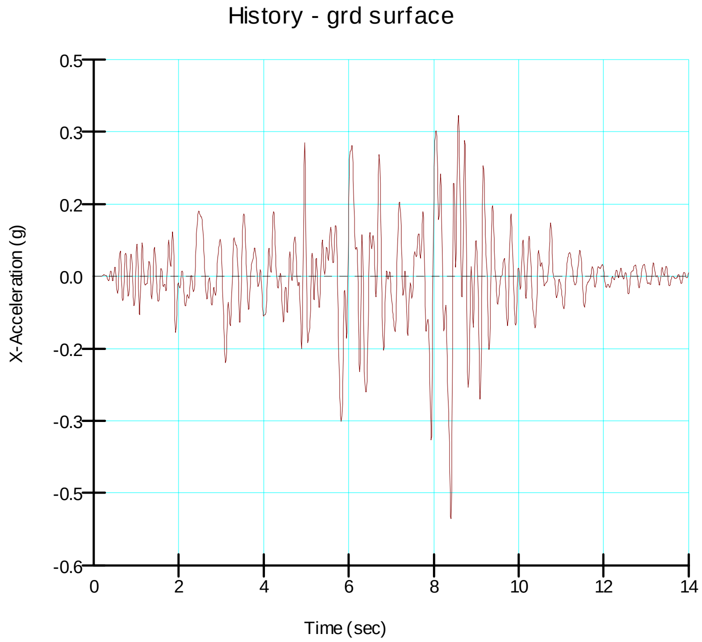

Figure 8 Ground response at the ground surface

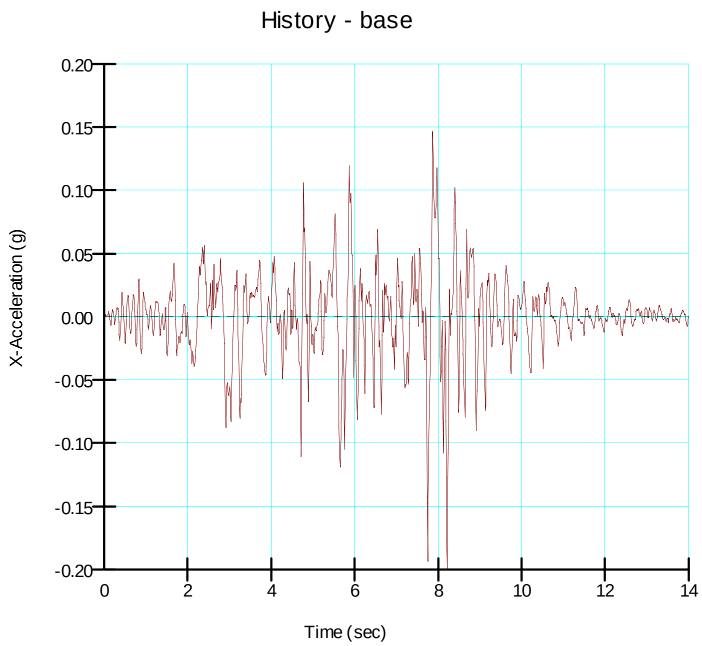

Figure 9 Replication of earthquake record at the fixed base

The lateral movement of the ground is illustrated by the displacement profiles in Figure 10. 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.

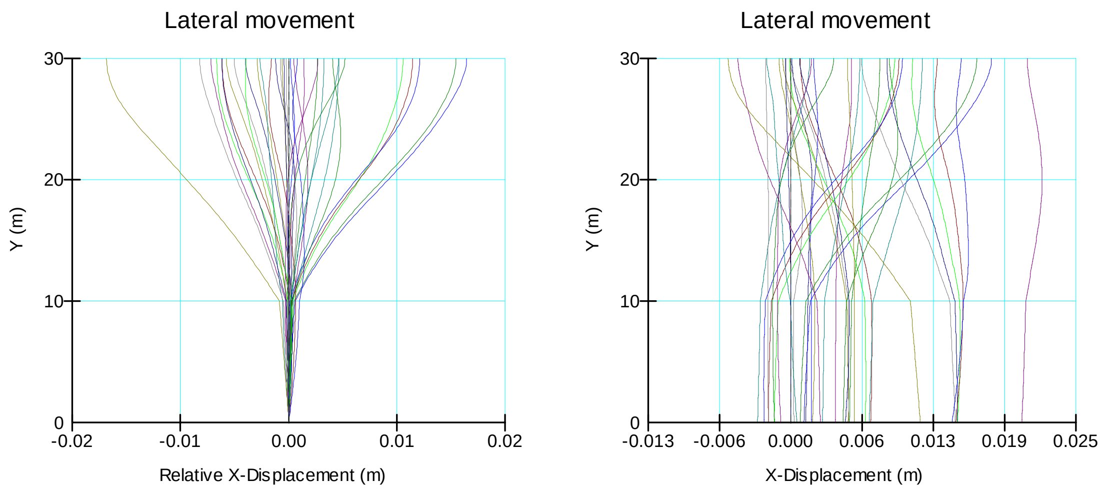

Figure 10 Lateral movement profiles

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-pressures.

6.3 Liquefaction

The resulting peak CSR profile is shown in Figure 11. 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 12, which marks the zone of liquefaction.

This is further illustrated by the effective stress profiles in Figure 13. The effective stress has essentially diminished to zero, which is the definition of liquefaction.

The related excess pore-pressure profile is shown in Figure 14.

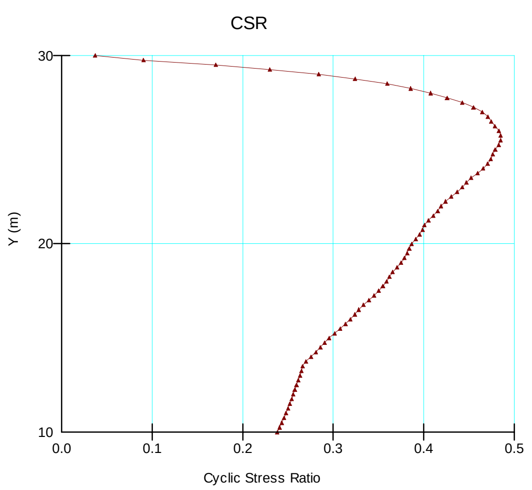

Figure 11 Peak CSR profile

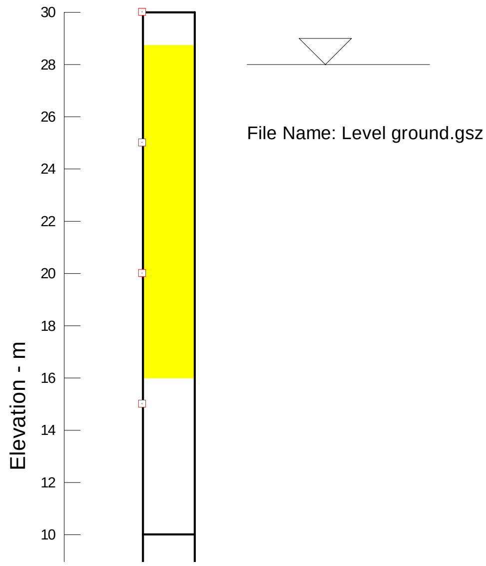

Figure 12 Zone of liquefaction

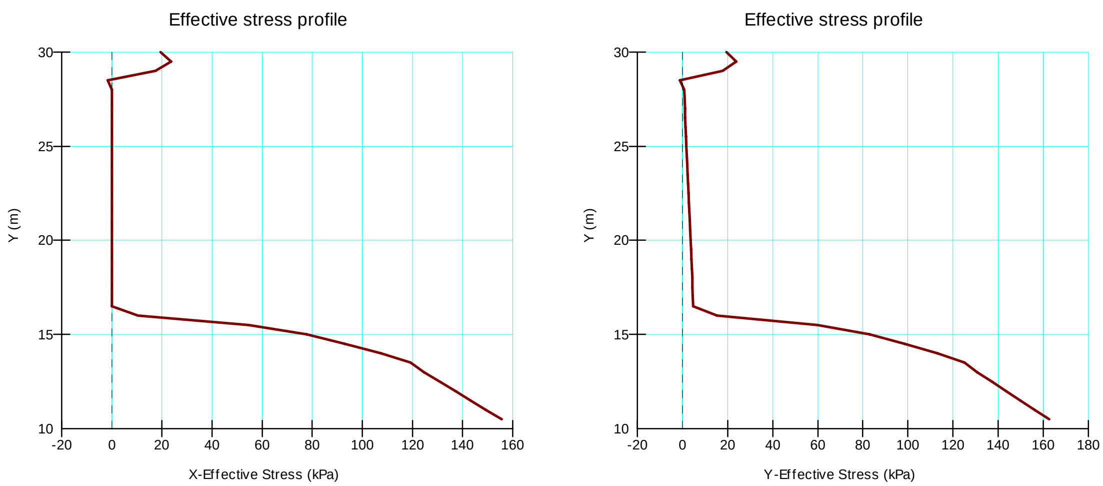

Figure 13 Effective stress profiles

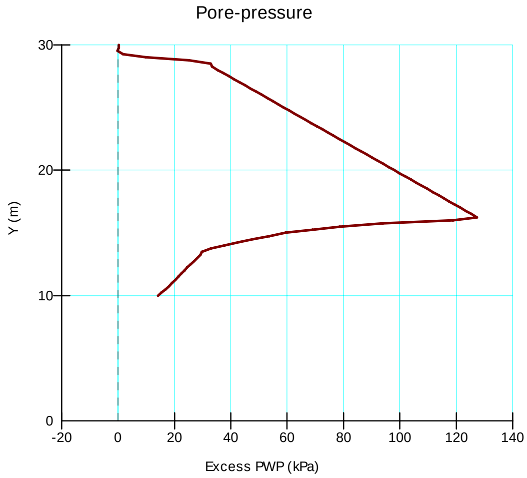

Figure 14 Excess pore-pressure in the sand

Non-linear analysis

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

In a Non-linear analysis, the developing excess pore-pressures are computed as part of each Δt time integration step. That is, excess pore-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-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.

6.4 Material properties

The G_{max} function (Figure 4) 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 Ø´, which in this example are zero and 34 degrees.

The Non-Linear method in QUAKE/W uses the MFS (Martin Finn Seed) pore-pressure model. To use this pore-pressure model, it is necessary to specify the functions in Figure 15 and Figure 16.

Figure 15 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).

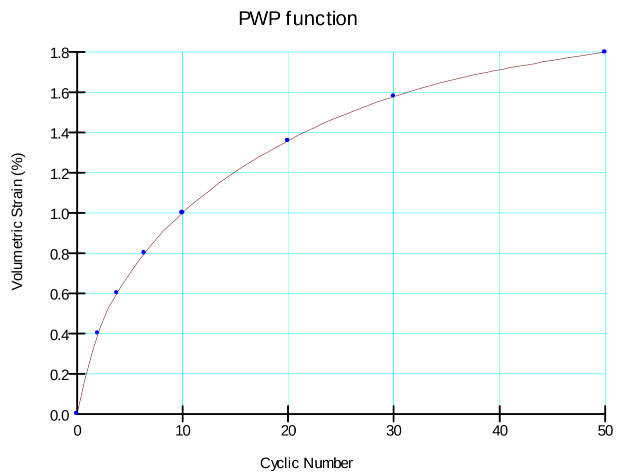

Figure 15 Volumetric strain versus stress cycles

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.

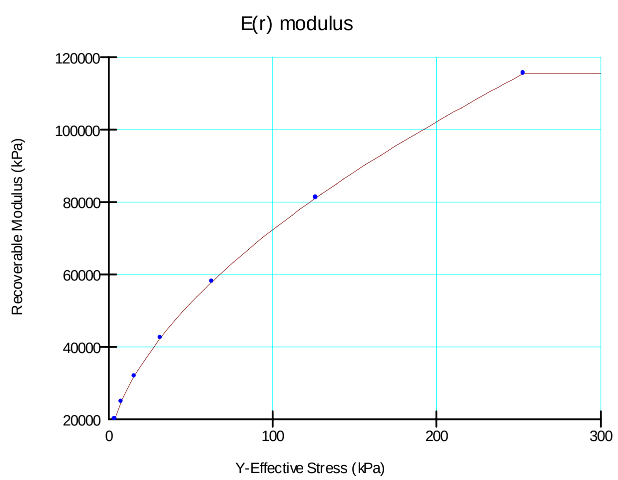

Figure 16 Recoverable modulus function

6.5 Response to the earthquake shaking

Figure 17 shows the acceleration versus time response at the ground surface. 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.

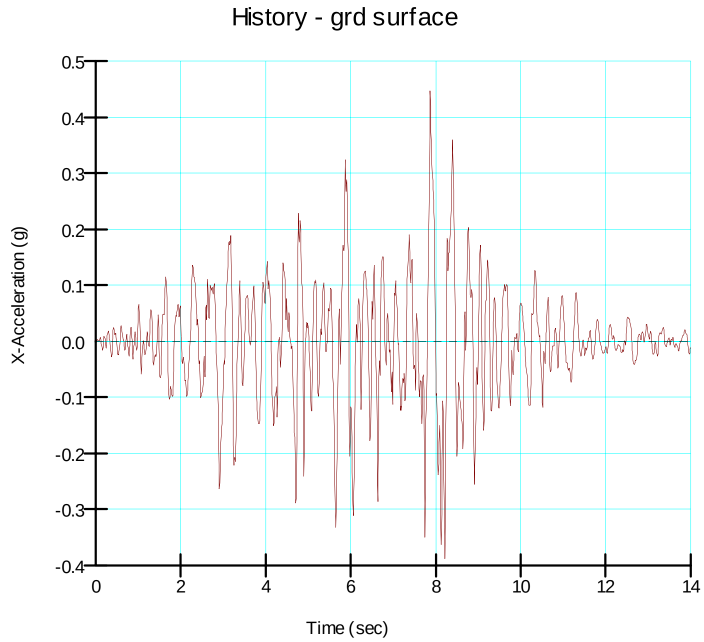

Figure 17 Ground response at the ground surface from the Non-Linear analysis

The relative lateral movements are illustrated in Figure 18.

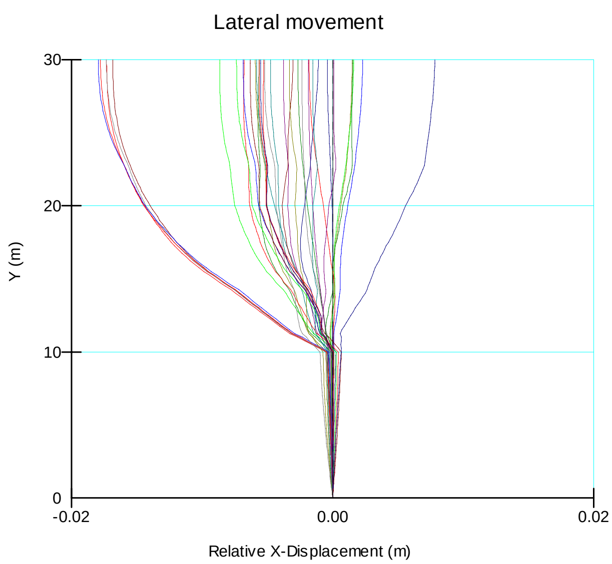

Figure 18 Relative lateral movement profiles from the Non-Linear analysis

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.

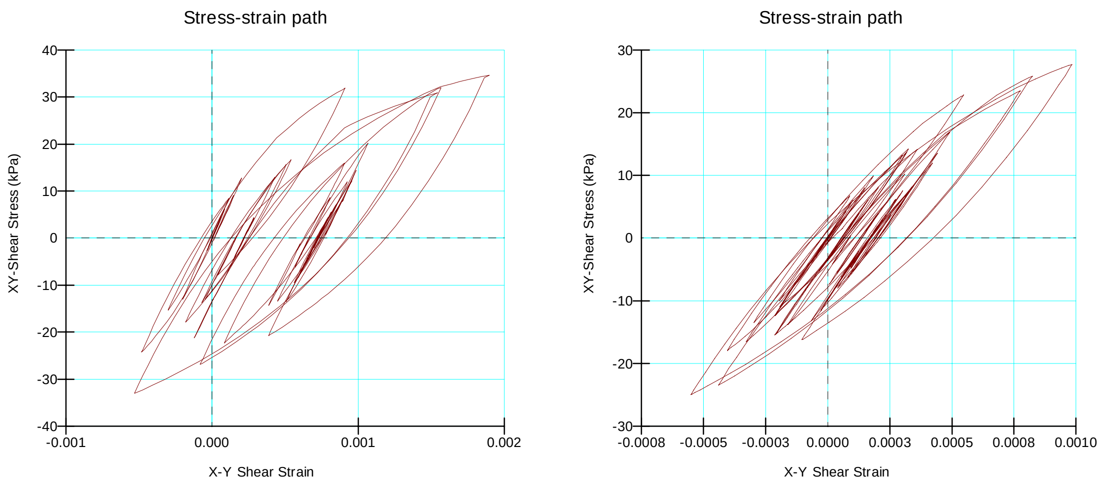

Figure 19 Stress-strain paths at Elevation 15 and 20 metres

6.6 Liquefaction

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.

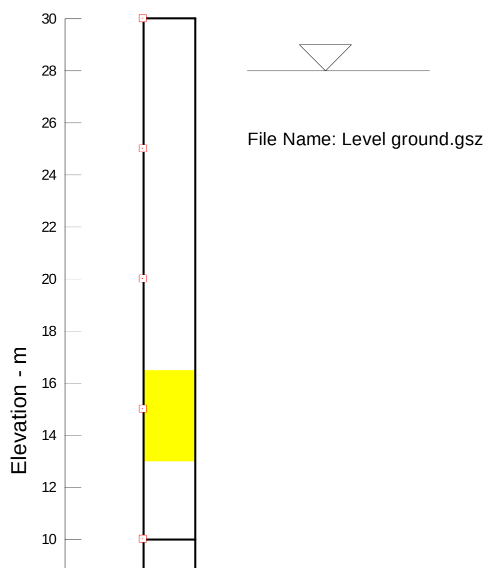

Figure 20 Liquefaction zone

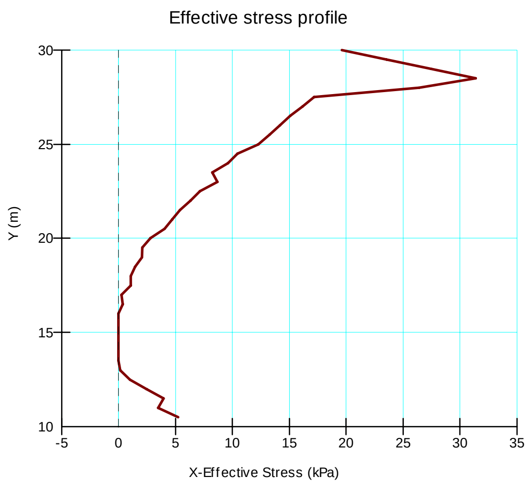

Figure 21 Horizontal effective stress profile

Figure 22 illustrates how the excess pore-pressure developed in the liquefied zone during the shaking. Note how the pore-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.

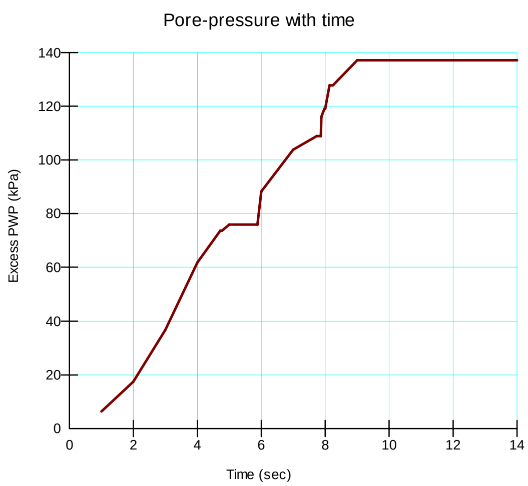

Figure 22 Development of excess pore-pressure with time during the shaking

7 Concluding remarks

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