

Permanent Deformations due to Inertial Forces

1 Introduction

This example demonstrates how the results of a QUAKE/W analysis can be used in conjunction with SLOPE/W to estimate the permanent deformations that may occur as a result of the inertial forces associated with an earthquake.

This type of permanent deformation analysis is referred to as a Newmark analysis. The premise of a Newmark analysis is that during an earthquake there will be short moments in time when the inertial forces (mass times acceleration) plus the initial static forces will exceed the available shear resistance, and during these times the temporary loss of stability will lead to un-recoverable deformations. The accumulation of the un-recoverable deformations will manifest itself as permanent deformation after the shaking has stopped.

The details of the implementation for this type of analysis are presented in the SLOPE/W Engineering Book. Only the highlights of an illustrative example are presented here.

A similar example is presented as part of the SLOPE/W group of examples. A variation of the SLOPE/W example is presented to enhance the QUAKE/W example list, and for convenient reference when one is examining the QUAKE/W features and capabilities.

Figure 1 presents the simple slope used in this illustrative analysis. Under static conditions, the factor of safety is about 1.2 (1.194). The material properties used can be viewed in the associated data file.

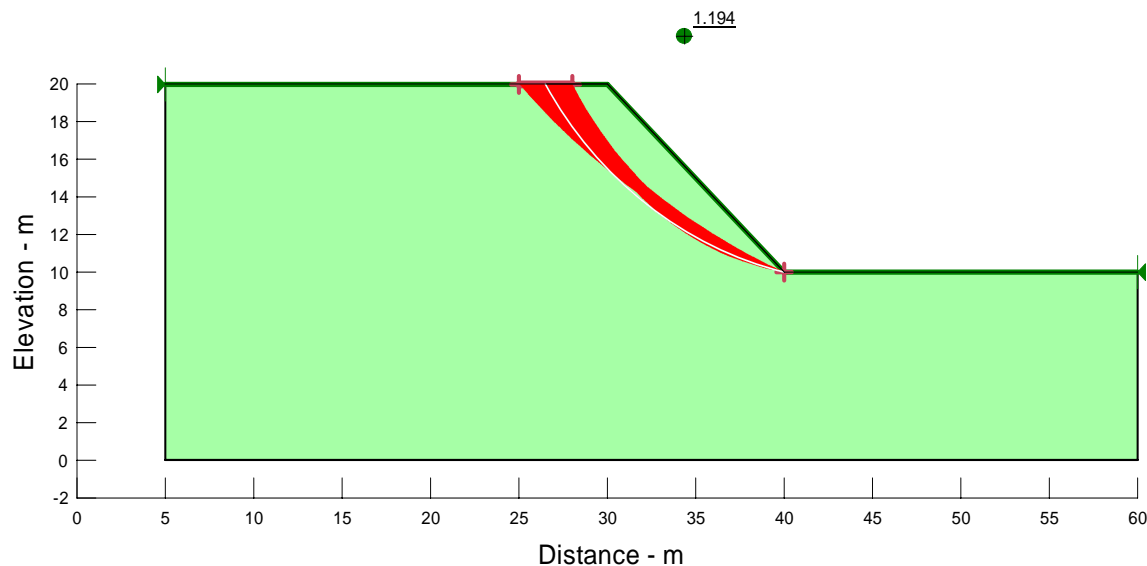


Figure 1 Stability of slope under static conditions

2 Initial insitu stresses

The first step is to establish the insitu state of stress in the ground that exists before the earthquake occurs and shakes the ground. In this case, this is done with the QUAKE/W Initial static type of analysis, which basically involves doing a simple gravity turn-on type of analysis. The results are the most conveniently inspected by creating contour plots of the various stress components. Figure 2 shows a typical example.

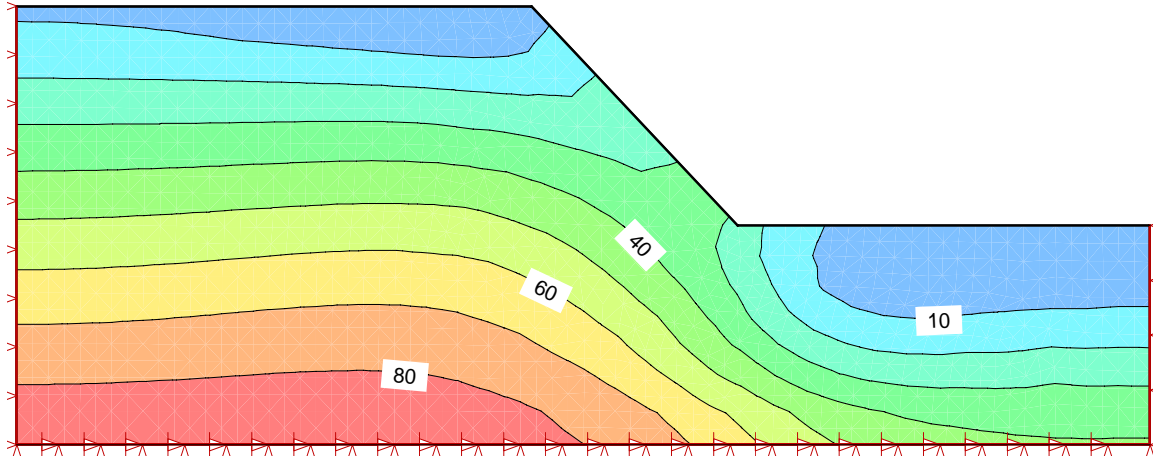


Figure 2 Maximum static shear stress contours

3 Shaking analysis

The next step is to subject the slope to an earthquake with a time history record shown in Figure 3. The peak acceleration is 0.4 g at about the 2-sec mark in the 10 seconds of shaking.

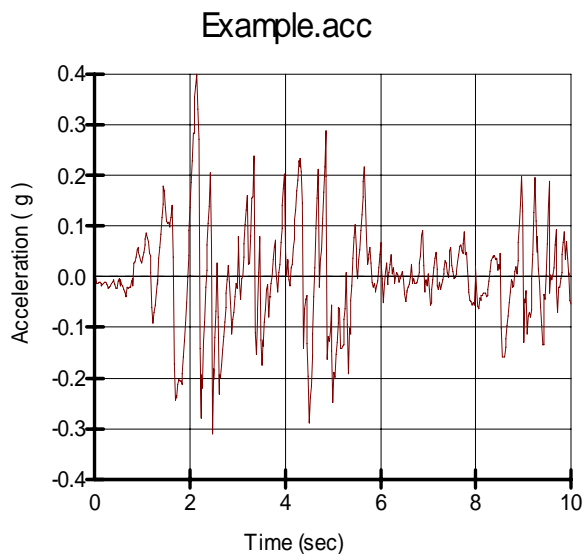


Figure 3 Earthquake time history record

Only linear-elastic soil properties are used here in this simple illustrative example.

It is intuitively obvious that the earthquake inertial forces will pull the slope in both the up-slope direction and in the down-slope direction. This is illustrated in Figure 4 and in Figure 5. Shown as well in these figures are the velocity and acceleration vectors. Note that the vectors are not in the same direction at any instance in time.

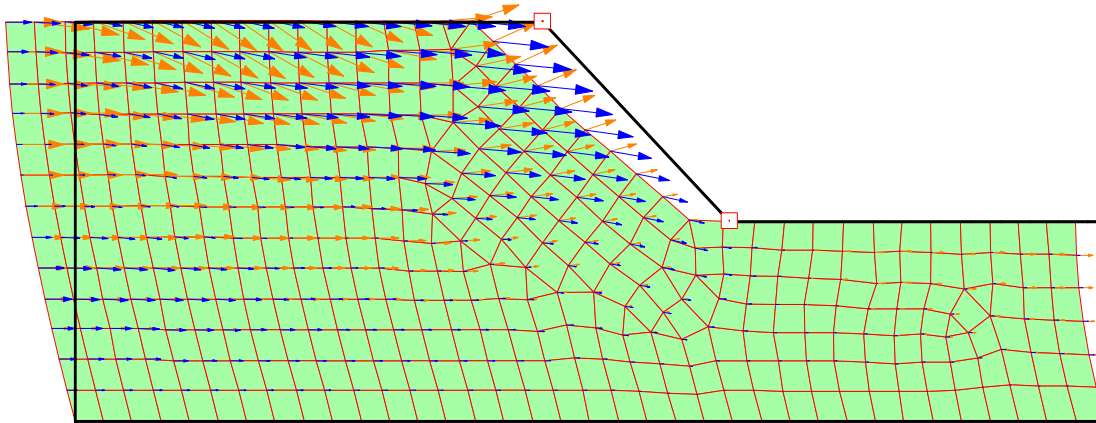


Figure 4 Displacement at the 1.60 second mark (100x exaggeration)

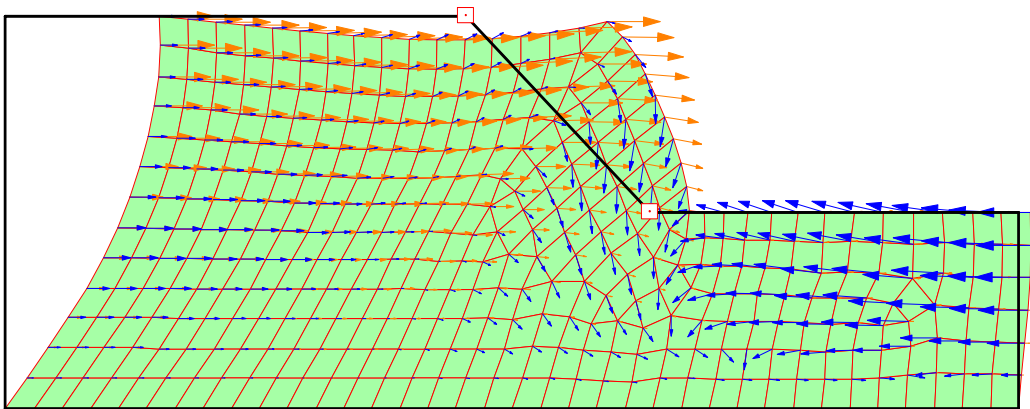


Figure 5 Displacement at the 2.40 second mark (100x exaggeration)

From the illustrations in the above two figures, it is easy to visualize that the factor of safety will go up and down during the shaking. The objective is to determine how many times and for how long the factor of safety is below 1.0 when there a momentary loss of stability.

The earthquake data for this record has a constant time interval of 0.02 seconds. For 10 seconds, this means there are 500 data points. The output data is saved to file only every 10th time step plus at 20 of the highest peaks in the record.

4 Permanent deformation analysis

The details of how finite element-computed stresses can be used in SLOPE/W to compute safety factors are presented in the SLOPE/W Engineering Book. It is sufficient to say here that for each trial slip surface, SLOPE/W computes the mobilized shear and normal stress at the base of each slice. The normal stress is then used in conjunction with the specified strength parameters to compute the available shear resistance at the base of each slice. A ratio of the summation of the available shear resistance to the summation of the mobilized shear is taken as the safety factor.

For a Newmark-type analysis, the soil strength is deemed to remain constant during the shaking (undrained behavior). The strength is therefore computed on the basis of the initial static stresses. Only the mobilized shear is re-computed for each time step that the data is saved to file.

The permanent deformation is computed for 18 trial slip surfaces in this example.

The largest computed deformations occur for Slip Surface 2. The static factor of safety for this slip surface is 1.236, as shown in Figure 6.

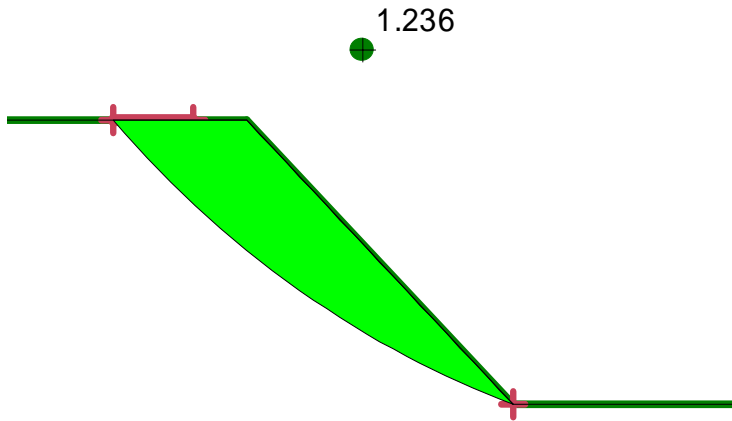


Figure 6 Slip surface with the largest deformation

Figure 7 presents the variation in the safety factors during the shaking. Note that there are moments when the factor of safety is less than unity (1.0), indicating that there are moments when the slope is temporarily unstable.

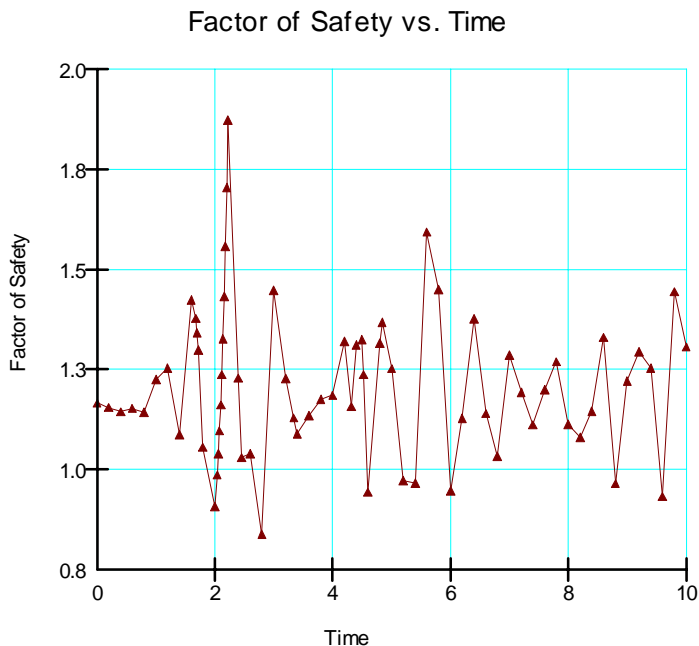


Figure 7 Variation in safety factors during the shaking

SLOPE/W computes the so-called yield acceleration from the data in Figure 8. The yield acceleration occurs where the factor of safety is 1.0. In this case, the yield acceleration is about 0.11g.

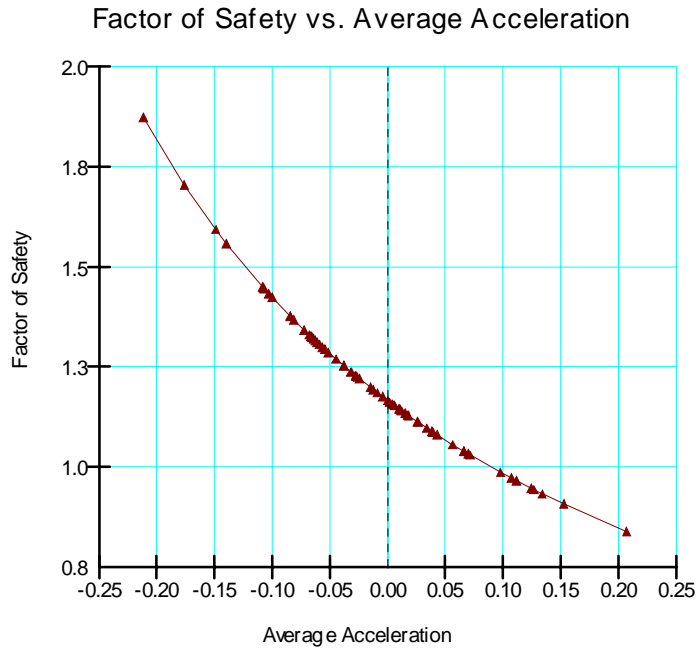


Figure 8 Factor of safety versus the average acceleration

Once the yield acceleration is known, SLOPE/W integrates the area under the curve in Figure 9, where the acceleration is greater than the yield acceleration, which in this case is 0.11 g. The integrated area gives the velocity as shown in Figure 10.

Integrating the area under the velocity curve gives the accumulated deformation, as shown in Figure 11.

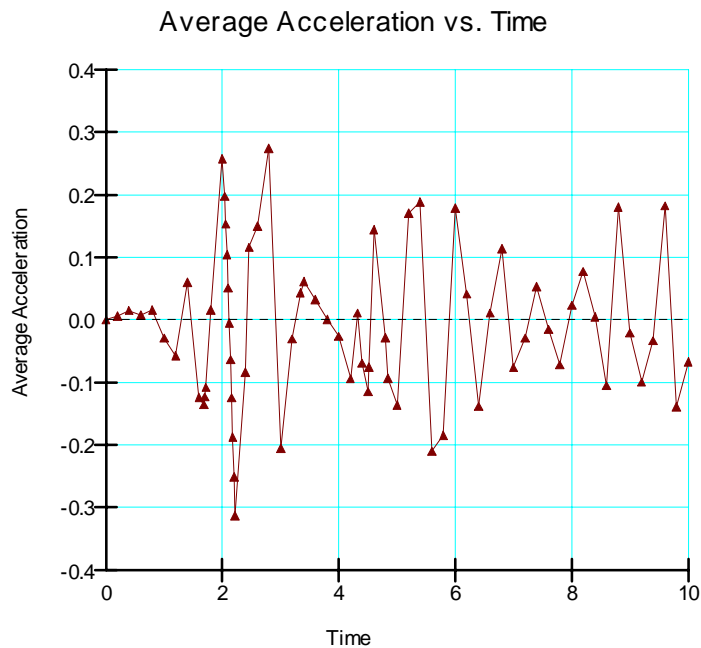


Figure 9 Average acceleration with time

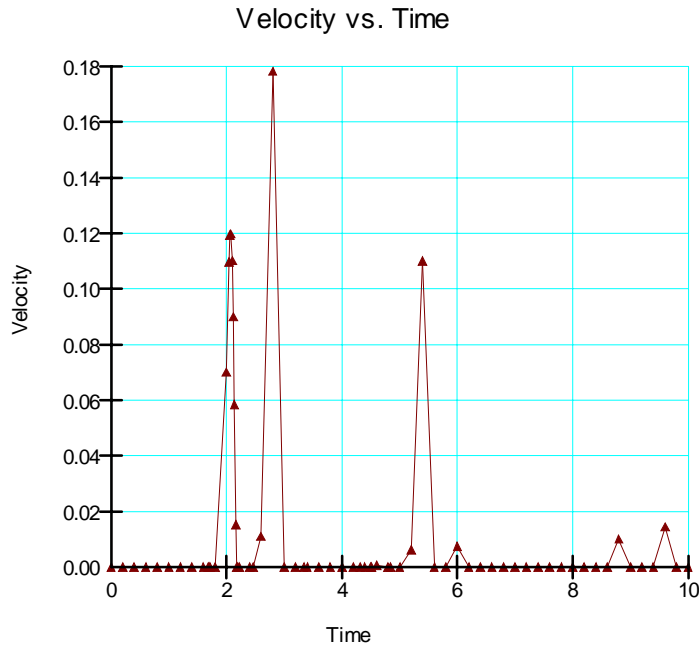


Figure 10 Velocity during moments of temporary loss of stability

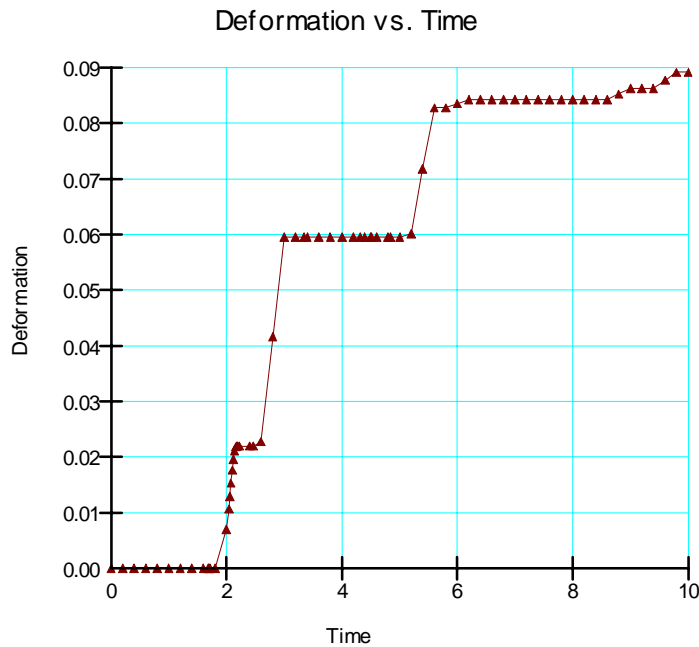


Figure 11 Accumulated deformations during moments of temporary loss of stability

In summary, this analysis indicates that there could be about 90 mm of permanent deformation of this slope if it were to be subjected to the earthquake.

The movement would be along the trial slip surface. In this case, with the slip surface being so steep, most of the movement would manifest itself as vertical movement although there could be a slight amount of rotational movement as well.

5 Closing remarks

It is vitally important to be mindful of the fact that a Newmark analysis involves only inertial forces and is applicable only to cases where there will not be a significant loss in shear strength and the generation of significant excess pore-pressures.

The Newmark analysis is very computationally demanding. For each trial slip surface, SLOPE/W computes a factor of safety for each QUAKE/W time step for which the data was saved. The computing time multiplies very quickly if there are a lot of QUAKE/W data files and many trial slip surfaces.

The recommended procedure is to establish the critical slip surface first, based on the initial static stresses. Then select a few trial slip surfaces around the static critical slip for a Newmark deformation analysis.

The QUAKE/W – SLOPE/W integration makes it possible to do a Newmark-type permanent deformation analysis for any potential slip surface.