Newmark Deformation Analysis

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Introduction

SLOPE/W can use the results from a QUAKE/W dynamic analysis to examine the stability of earth structures subjected to earthquake shaking. This example illustrates the use of static and dynamic ground stresses computed by QUAKE/W in a SLOPE/W analysis. Given these stresses, SLOPE/W uses a procedure similar to the Newmark method (Newmark, 1965) to analyze stability fluctuation during the earthquake and estimate the resulting permanent deformation.

Background

A Newmark analysis is based on the idea of a block sitting on an incline. During an earthquake, there may be temporary inertial forces (mass times acceleration) that cause the block to slide down the incline. The corresponding permanent deformation is the accumulation of the short sliding instances. The acceleration at which movement occurs is the yield acceleration (a_y).

In GeoStudio, a static QUAKE/W analysis produces the initial stresses before shaking, followed by a dynamic QUAKE/W analysis simulating the earthquake accelerations and corresponding stresses over time. Similar to the finite element stability method, SLOPE/W can use these results to determine the stresses at the base of each slip surface slice and compute a factor of safety for the slip surface. The shear resistance used in the factor of safety calculation is assumed constant over time (corresponding to undrained conditions), and is computed based on the initial static stresses. The factor of safety is determined for each time step in the dynamic QUAKE/W analysis.

The factor of safety generally oscillates over time due to the applied inertial forces, so determining the overall slope stability during shaking is often challenging. However, the results can be used to assess deformation of the slope. To do so, the additional stresses throughout the domain due to earthquake shaking (i.e., the dynamic portion of the computed stresses), $\sigma_{dynamic}$, are determined by:

$$\sigma_{dynamic} = \sigma_{Q_d} - \sigma_{Q_s}$$ **Equation 1**

where σ_{Q_d} and σ_{Q_s} are the stresses throughout the domain computed by the dynamic and static QUAKE/W analyses, respectively. The dynamic stresses can be used to determine the mobilized dynamic shear at the base of each slip surface slice. Integration of these values along the slip surface provides the total dynamic mobilized shear, $S_{m_{dynamic}}$, which represents the additional mobilized shear stress resulting from the earthquake accelerations.

An average acceleration, a, of the sliding mass, m, can be calculated as:

$$a = \frac{S_{m_{dynamic}}}{m}$$ **Equation 2**

where the total mass of the sliding zone is the summation of the slice masses. The average acceleration computed at each time step in the dynamic QUAKE/W analysis and the corresponding factor of safety are plotted (Figure 1) to determine the acceleration associated with a factor of safety of 1.0. This value is the yield acceleration, a_y. If the factor of safety during the earthquake never drops below 1.0, then the calculated Newmark deformation is zero. This is often the case when the static factor of safety is high.

The pseudo-static seismic coefficient, k, that results in a factor of safety of 1.0 is determined by:

$$k_y = \frac{a_y}{g}$$ **Equation 3**

where the yield seismic coefficient is a ratio of the yield acceleration to the gravitational constant, g.

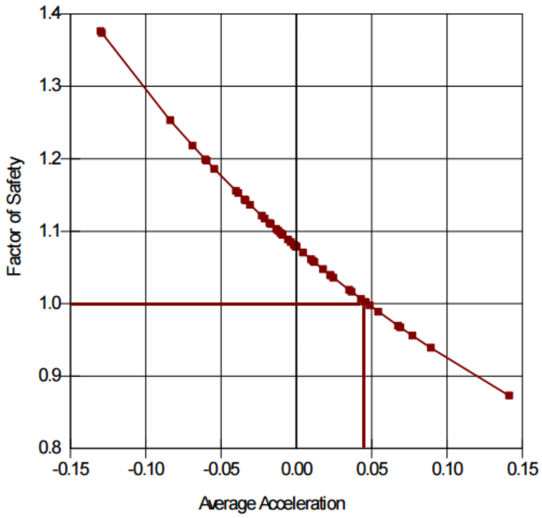


Figure 1: Comparison of the computed factor of safety and average acceleration.

The average acceleration may also be plotted over time to generate an acceleration time history (Figure 2). The acceleration time history generally has very small time intervals (e.g., 0.02 s) based on the specified earthquake record. Thus, the computations associated with a Newmark Deformation SLOPE/W analysis can be very demanding, especially if many QUAKE/W time steps are saved to the file and there are many trial slip surfaces. To limit the computation, it is advisable to save the acceleration results after multiple steps (e.g., every 10 steps), and to compute the permanent deformation for a limited number of slip surfaces (e.g., the 10 slip surfaces with the lowest static factor of safety).

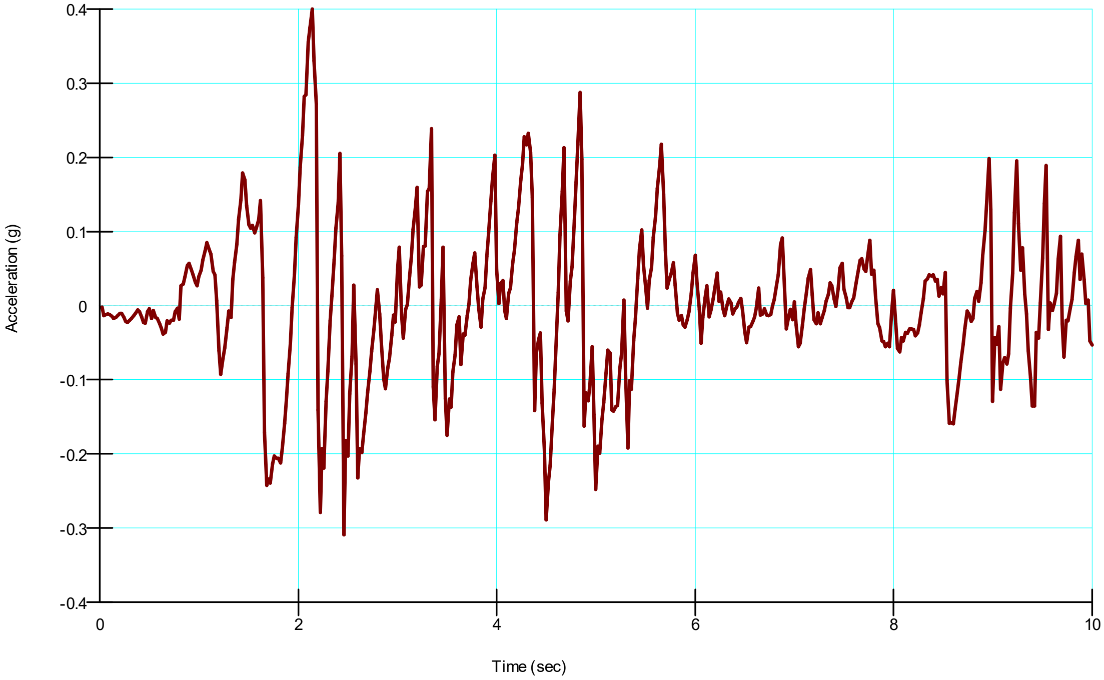


Figure 2. Earthquake acceleration time history record.

Integration of the acceleration time history plot for all time steps with an acceleration above the yield value results in the velocity of the sliding mass over time. Further integration of the velocity over time graph produces deformation over time. This deformation is parallel to the slip surface, resulting in both rotational and translational movement. Note that any negative accelerations greater than the yield value may indicate up-slope movement; however, these movements are assumed to be negligible and are ignored.

A Newmark type of analysis is only applicable under the following conditions:

a) Minimal degradation in shear strength (<15%) during shaking;
b) Shaking does not generate excess pore-water pressures, as excess pore-water pressures are often associated with significant shear strength loss; and
c) The soil grain structure remains intact, as collapse of the soil structure (i.e., liquefaction) also causes significant shear strength loss.

Numerical Simulation

In this example the initial stresses are determined using an *Initial Static* QUAKE/W analysis (Figure 3, Analysis 1). A *QUAKE/W Stress* type SLOPE/W analysis uses the static stresses generated by Analysis 1 to determine the critical slip surface before earthquake shaking (Analysis 1a). An *Equivalent Linear Dynamic* analysis computes the stresses during shaking given the initial conditions provided by Analysis 1. The final SLOPE/W analysis, *QUAKE/W Newmark Deformation* analysis type, uses the methods described above to compute factor of safety over time, the yield acceleration, and the resulting deformation of the slope.

Analyses

1 - Initial in-situ stresses
    1a - Static stability
    2 - Shaking analysis
        2a - Permanent deformation

Figure 3. Project analysis tree.

The domain comprises a steep, homogenous slope (Figure 4). For simplicity, pore water pressure conditions were not defined in this project. For both of the QUAKE/W analyses, the material is defined by the Linear Elastic material model with a unit weight of 18 kN/m^3, a Poisson's ratio of 0.334, a damping ratio of 0.1, and a maximum shear modulus of 20,000 kPa. The linear elastic material model was selected for this example as it is the simplest constitutive model and does not require an iterative procedure to solve; however, it is generally not applicable to field problems given the tendency for non-linear behavior during shaking.

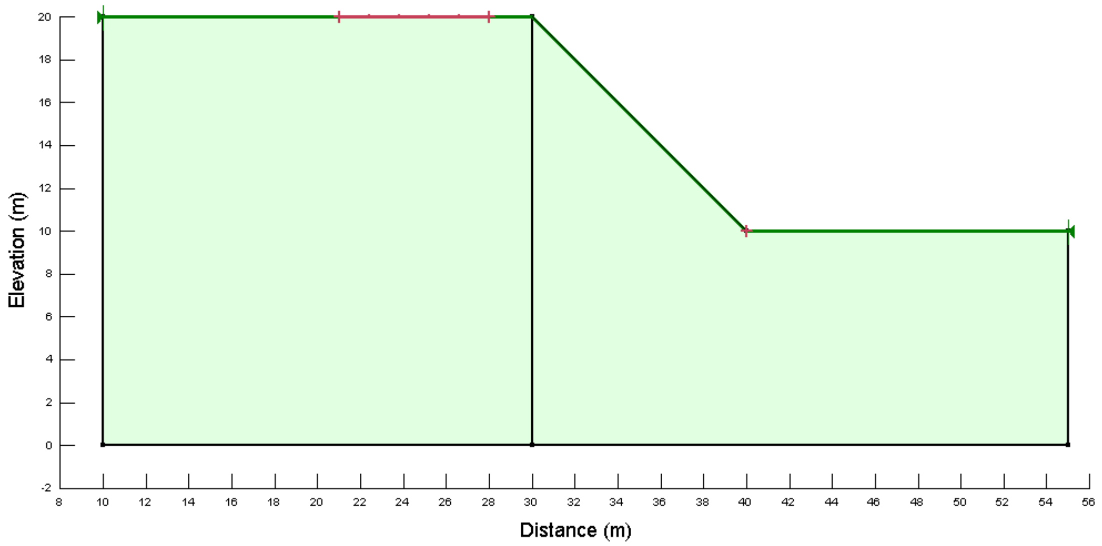
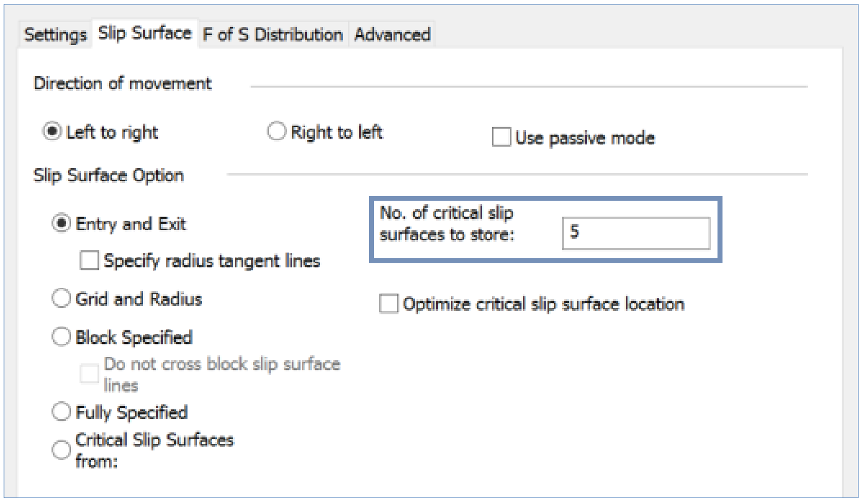


Figure 4. Problem configuration.

The Mohr-Coulomb material model is used in both SLOPE/W analyses with a friction angle of 28° and cohesion of 8 kPa. The first SLOPE/W analysis, representing static conditions, uses the Entry and Exit method to define the trial slip surfaces. All of the trial slip surfaces go through the slope toe (Figure 4). Only the five slip surfaces with the lowest computed factors of safety are saved to the file, as specified on the Slip Surface tab for Analysis 1a (Figure 5). These five slip surfaces are the only ones considered in the second SLOPE/W analysis for computing Newmark deformation (Figure 6).



Direction of movement

● Left to right ○ Right to left ☐ Use passive mode

Slip Surface Option

● Entry and Exit

☐ Specify radius tangent lines

○ Grid and Radius

○ Block Specified

☐ Do not cross block slip surface lines

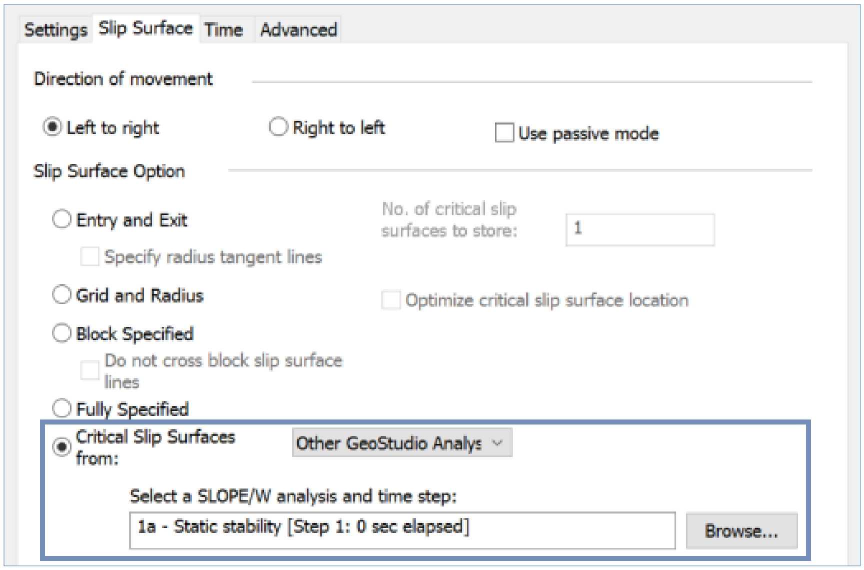
○ Fully Specified

○ Critical Slip Surfaces from:

No. of critical slip surfaces to store: 5

☐ Optimize critical slip surface location

Figure 5. Analysis 1a slip surface definition, including number of critical slip surfaces to save.



Direction of movement

● Left to right ○ Right to left ☐ Use passive mode

Slip Surface Option

○ Entry and Exit

☐ Specify radius tangent lines

○ Grid and Radius

○ Block Specified

☐ Do not cross block slip surface lines

○ Fully Specified

● Critical Slip Surfaces from: Other GeoStudio Analys

Select a SLOPE/W analysis and time step: 1a - Static stability [Step 1: 0 sec elapsed]

No. of critical slip surfaces to store: 1

☐ Optimize critical slip surface location

Figure 6. Analysis 2a slip surfaces definition, using the saved critical slip surfaces from Analysis 1a.

Results and Discussion

The initial analysis generates the stress state throughout the domain given static conditions (Figure 7). The critical factor of safety based on the static stresses is 1.188 (Figure 8), using the Finite Element slope stability method (see the SLOPE/W example: Finite Element Stresses). Thus, the total mobilized shear is relatively close to the total shear resistance along the critical slip surface before applying earthquake shaking to the slope.

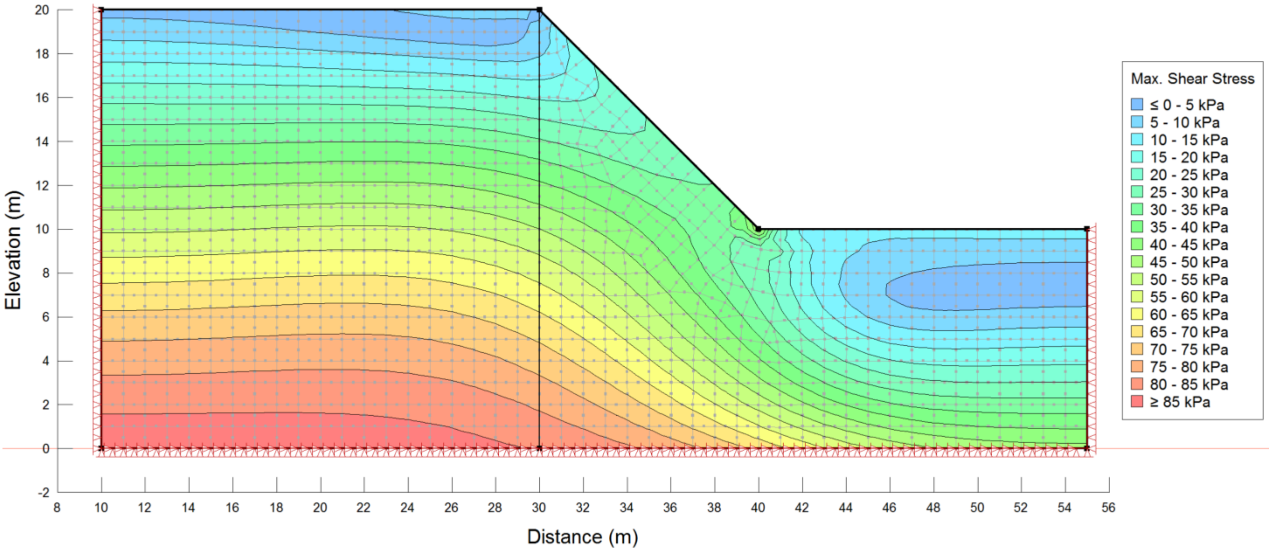


Figure 7. Maximum shear stress contours generated by Analysis 1a.

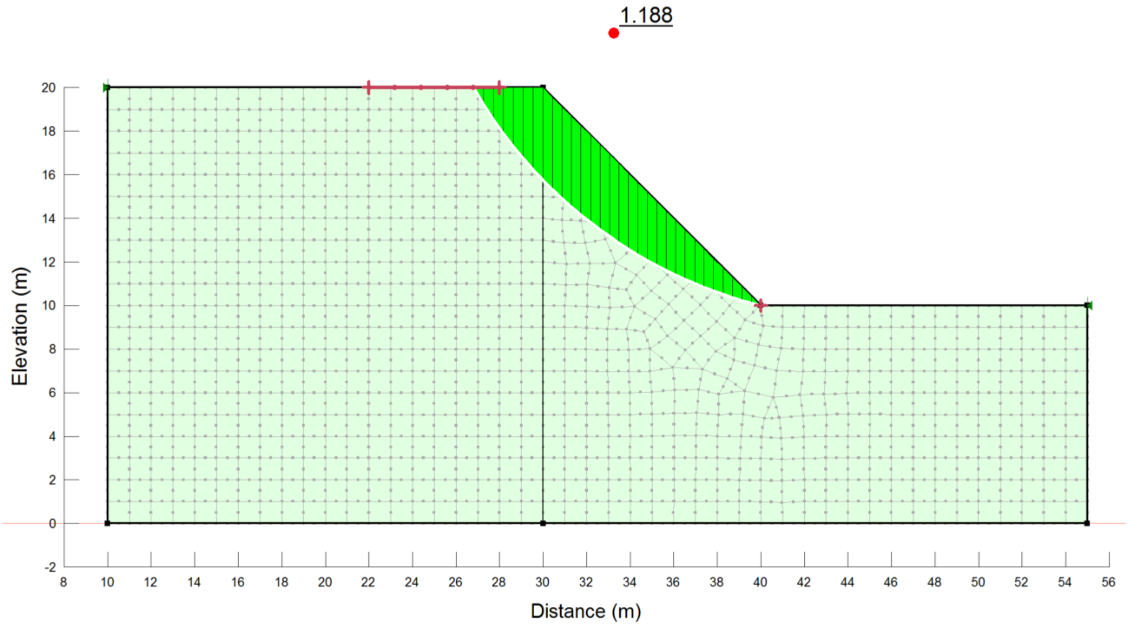


Figure 8. Factor of safety for the critical slip surface based on the static stress conditions (Analysis 1a).

The results from the dynamic QUAKE/W analysis demonstrate that the earthquake accelerations generate both down-slope some and up-slope motion (Figure 9). Down-slope motion is associated with a decrease in the factor of safety, while up-slope motion causes an increase in stability. The dynamic QUAKE/W results also indicate that shear stresses in the slope are not uniform in either direction or over time. The shear stress profile through a vertical section of the domain (at the slope crest) illustrates shear stress variability with depth (Figure 10). Thus, a dynamic finite element analysis is necessary to capture variability in the ground stresses at any moment in time.

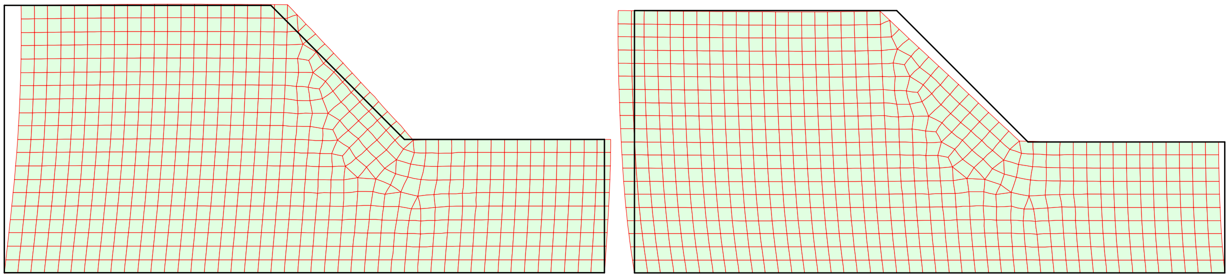


Figure 9. Example down-slope (left) and up-slope (right) motion generated by the dynamic QUAKE/W analysis (Analysis 2).

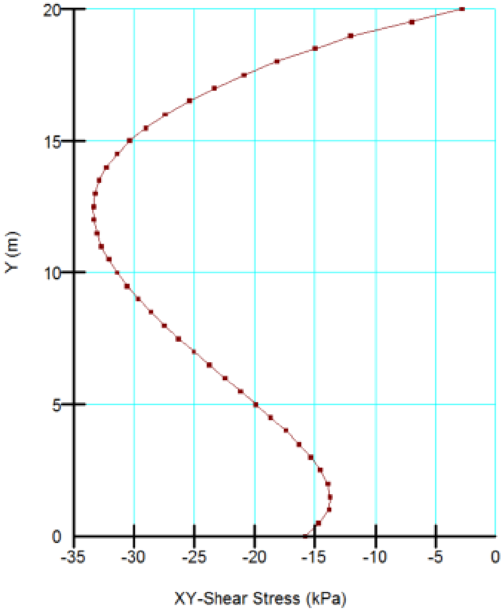


Figure 10. Shear stress profile along a vertical line from the slope crest generated by Analysis 2 at 2.46 seconds.

The factor of safety for the critical slip surface varies from 0.78 to 3.31 during shaking (Figure 11). As mentioned above, the factor of safety oscillates, going above and below the static factor of safety, and in some instances, below 1.0. The Newmark Deformation SLOPE/W analysis estimates how much movement likely occurred during periods when the factor of safety drops below 1.0. Graphing the factor of safety over average acceleration of the sliding mass provides a yield acceleration of approximately 0.1 m/s^2 for the critical slip surface (Figure 12).

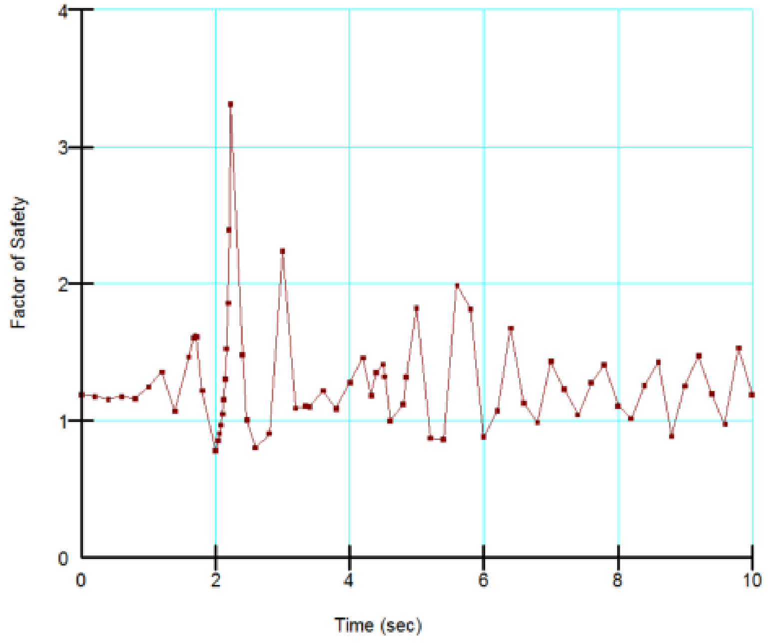


Figure 11. Factor of safety versus time from the Newmark Deformation SLOPE/W simulation (Analysis 2a).

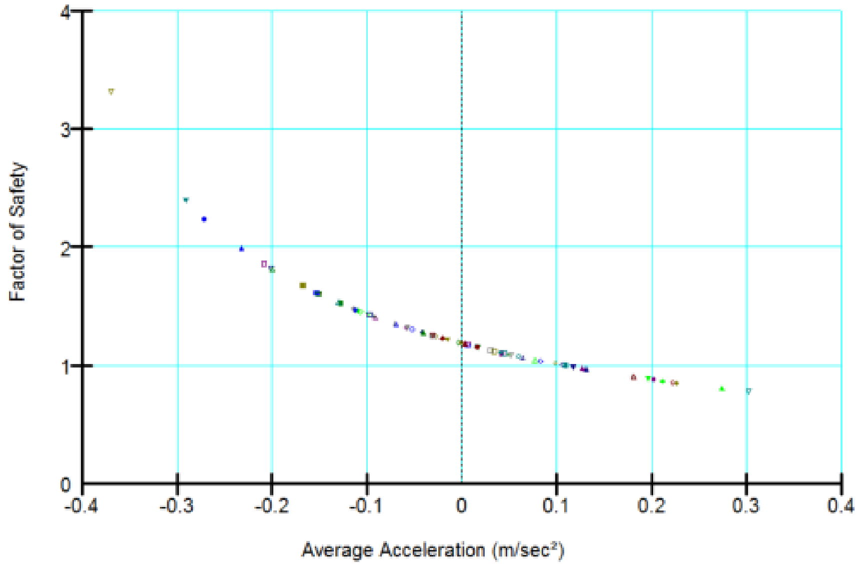


Figure 12: Factor of safety over average acceleration for the critical slip surface (in Analysis 2a).

The average acceleration of the sliding mass oscillates over time (Figure 13). Acceleration values below the negative yield acceleration (< -0.1 m/s^2) could potentially cause up-slope deformations; however, as mentioned above, these movements are ignored. Thus, only accelerations greater than 0.1 are assumed to result in permanent deformation of the slope (as indicated by the dashed line in Figure 13). Integrating the area under the acceleration time history plot when the average acceleration is greater than 0.1 produces the velocity over time associated with movement of the slope (Figure 14).

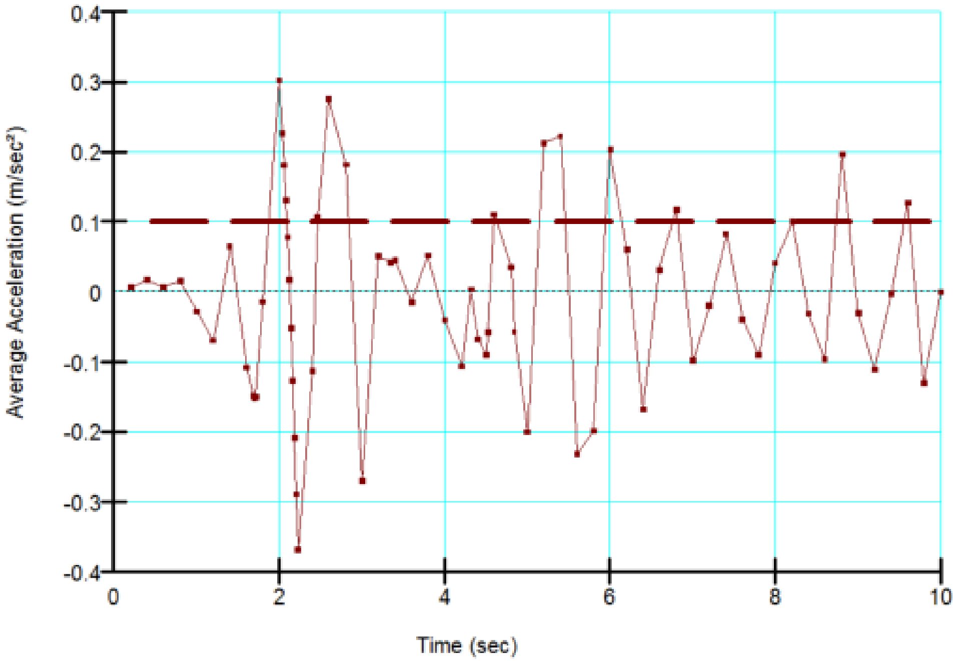


Figure 13. Average acceleration time history for the critical slip surface (Analysis 2a).

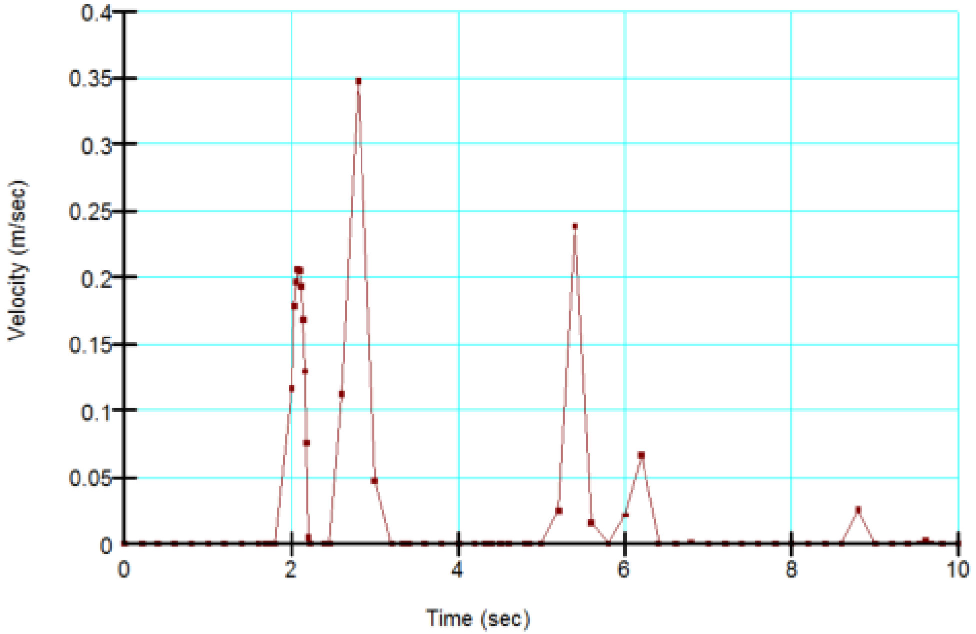


Figure 14. Velocity over time for the critical slip surface (Analysis 2a).

Integration of the velocity plot produces the permanent deformation of the slope over time (Figure 15). The earthquake shaking caused approximately 0.22 m of deformation over the course of the simulated period (10 s). Comparison of the deformation and acceleration plots illustrates that deformation increases when the average acceleration is above the yield value, as expected (Figures 13 and 15).

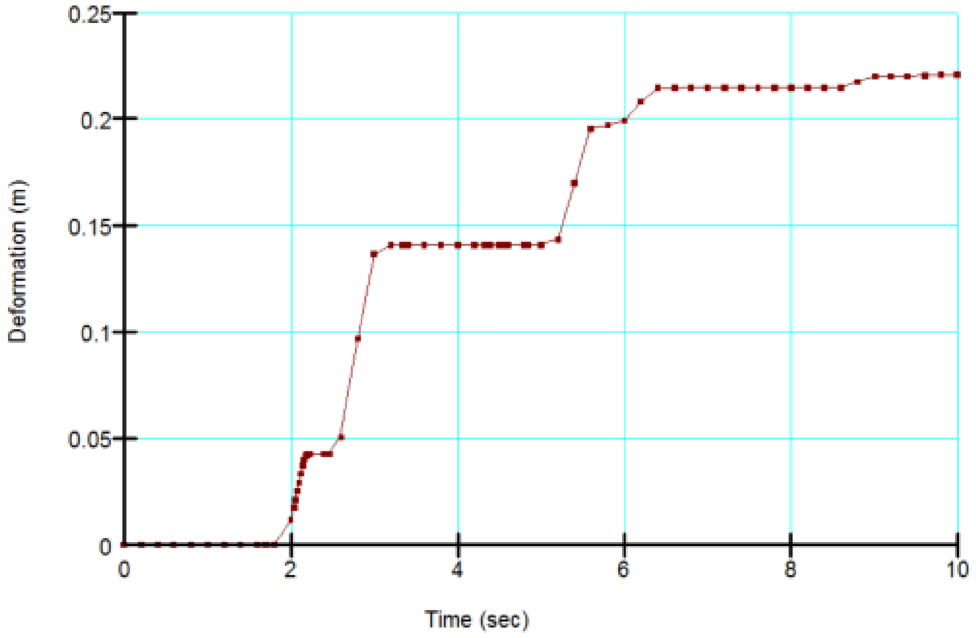


Figure 15. Cumulative deformation over time caused by accelerations greater than the yield acceleration (Analysis 2a).

Summary and Conclusions

This example demonstrates the use of a Newmark Deformation SLOPE/W analysis to assess the factor of safety over time during earthquake shaking. When the factor of safety is plotted over average acceleration of the sliding mass, the yield acceleration corresponds to a factor of safety of 1.0. This yield acceleration is used to determine the permanent deformation of the slope during shaking. In this example, the permanent deformation associated with the critical slip surface is 0.22 m. Newmark analyses only consider inertial forces and are therefore not intended to deal with issues like the generation of excess pore-water pressures and the potential for liquefaction.

References

Newmark, N.M. 1965. Effects of earthquakes on dams and embankments. Géotechnique, 15(2): 139-160.