

Waba Dam Permanent Deformation due to an Earthquake

1 Introduction

This example presents the results of a permanent deformation analysis of a low dam on a clay foundation. QUAKE/W is used to do a shaking analysis, and the results are then used in SIGMA/W to do a “Dynamic Deformation” type of analysis. The results are also compared with a Newmark-type of deformation analysis.

2 Waba dam

The Waba dam is a relatively low dam in Eastern Ontario, Canada built of clayey materials and founded on a deep deposit of marine clay (Law et al., 2000; Law et al. 2005). The dam has wide berms on both the upstream and downstream sides to achieve the required margins of safety against instability under static conditions because of the soft weak foundation. The dam is in an area of moderate seismicity and performance of the dam in the event of an earthquake has become an issue for the owners and operators.

The generation of excess pore-pressures and the associated possible liquefaction are not an issue at this site, due to the clay foundation and embankment. However, possible plastic yielding of the foundation soil during earthquake shaking and the resulting permanent deformation is a concern.

Figure 1 shows a cross-section of the dam. The embankment is only 11 m high with wide side berms 6 m high. The depth of the foundation clay is 66 m and the depth of the reservoir is only 8 m.

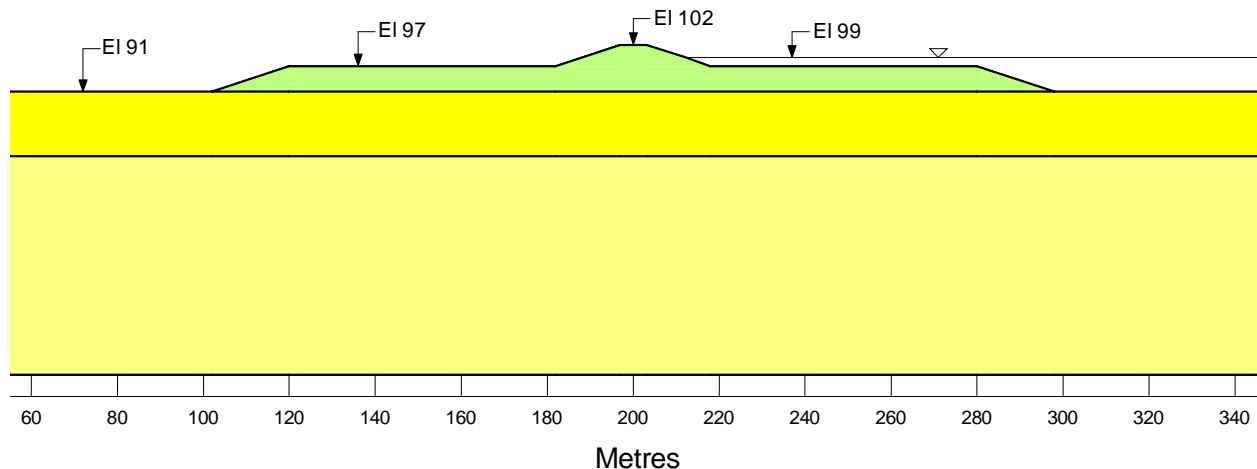


Figure 1 Waba dam cross-section

The embankment is characterized with an undrained strength of 100 kPa. The upper 15 m of the foundation clay as an undrained strength C_u equal to 35 kPa. Below that, the strength increases with depth up to 160 kPa at the base of the section. Since we are using only undrained strength, the analyses are done using total stress parameters; that is, pore-pressures are not considered in this study.

The undrained stiffness modulus E_u is defined as 900 times C_u . The stiffness correspondingly increases with depth as C_u increases with depth.

For the QUAKE/W dynamic analysis, the shear modulus G is required instead of the E modulus. G is computed from E by:

$$G = \frac{E}{2(1-\nu)}$$

The Poisson's ratio is taken to be 0.45.

3 Earthquake records

Two earthquake records were considered by Law et al. (2005). One is called a 'Near field' record and the other is called a 'Far field' record. The records are presented in Figure 2 and Figure 3. The Near field record has duration of only 2 seconds with a peak equal to 0.675g. The Far field record has a much longer duration of 16.1 seconds but the peak is only 0.325g.

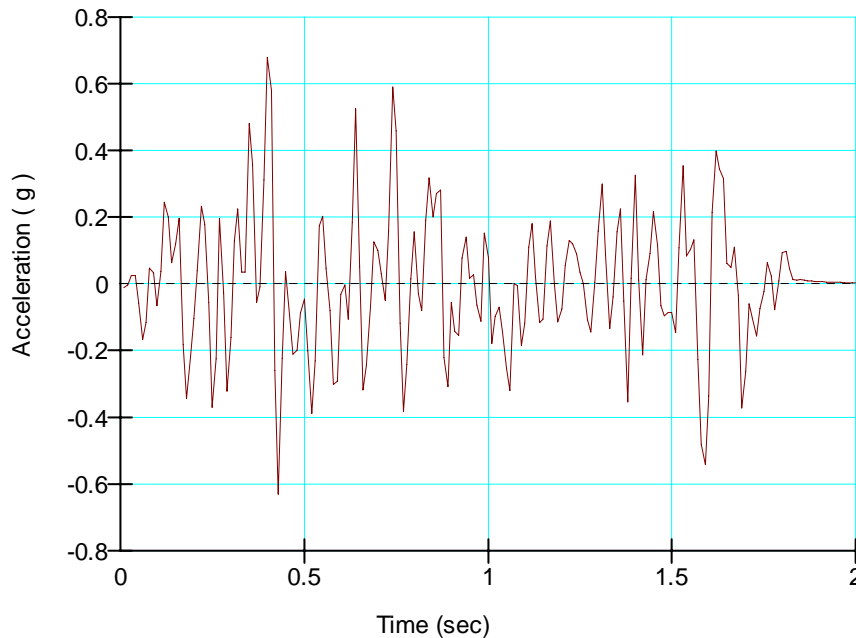


Figure 2 Near field earthquake record

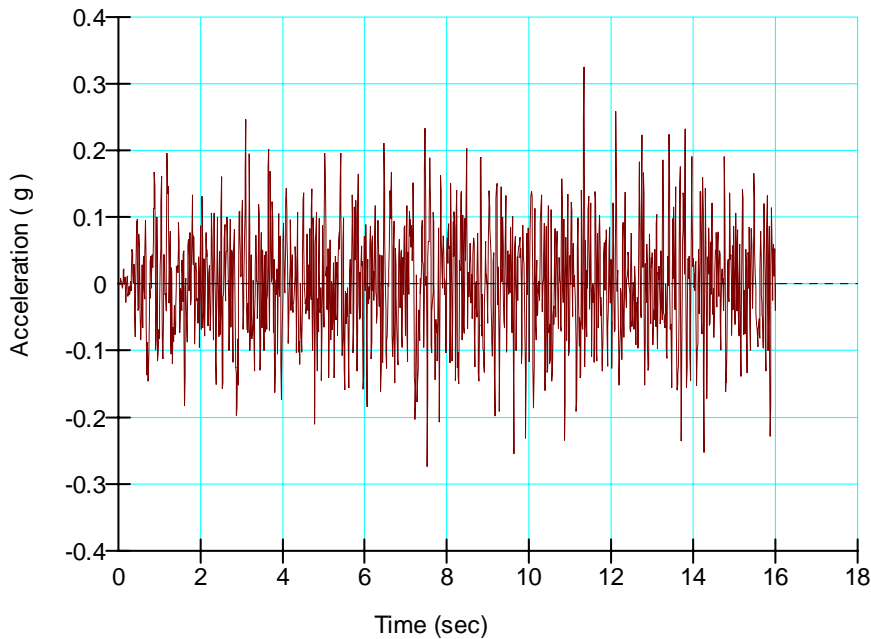


Figure 3 Far field earthquake record

4 Analysis tree

SIGMA/W, QUAKE/W and SLOPE/W are used in the analysis as shown by the following analysis tree. Each of the analyses is discussed as to its purpose.

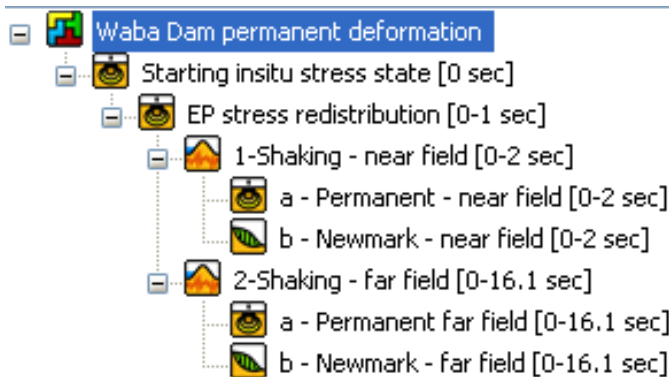


Figure 4 Waba dam analysis tree

5 Starting insitu stresses

The first step is to establish the long-term static stress insitu stress state. This is done with SIGMA/W using the *Insitu* analysis type. Notice the cross-hatching in Figure 5. This signifies that the gravitational self-weight is being applied by the specified soil unit weight. Also, notice the surface pressure that is being applied to represent the weight of the reservoir water. This is necessary in order to establish the correct total stresses in the ground. The fluid pressure is applied as hydrostatic boundary condition with a specified elevation of 91 m.

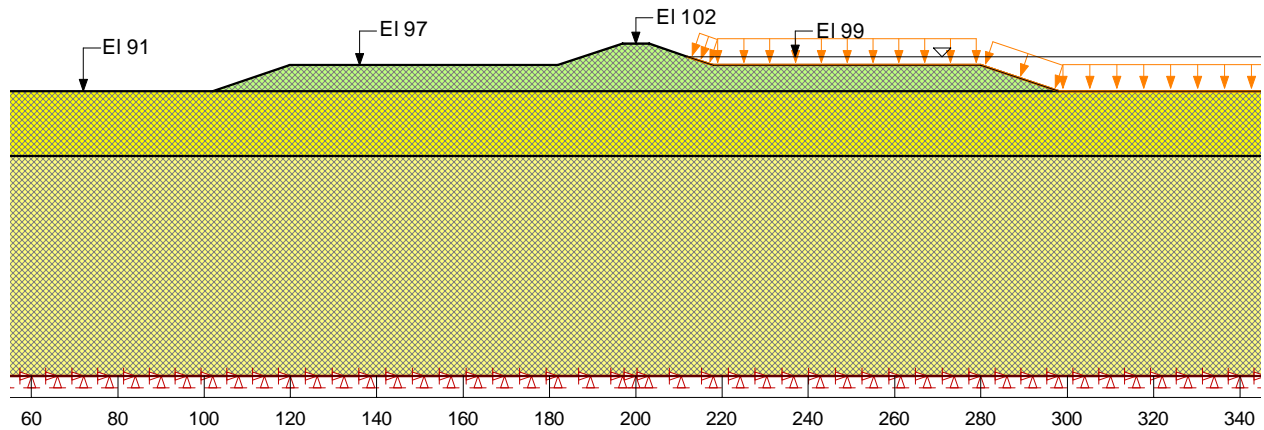


Figure 5 Setup to establish the starting insitu stress state

6 Stress redistribution

The *In situ* analysis type in SIGMA/W uses linear-elastic soil properties. This may result in some local stresses larger than the strength of the soil. To remove the overstressing, it is necessary to do a SIGMA/W *Stress Redistribution* analysis. The *Stress Redistribution* analysis uses elastic-plastic soil properties and redistributes the stresses so that there are no zones of overstressing. A redistribution analysis exhibits some deformations, which need to be removed before looking at plastic strains that may come from the earthquake shaking. In the QUAKE/W analysis, a check box is used to exclude cumulative values from the previous analysis.

7 Shaking analysis – Near field

Now that the insitu stresses have been established, the next step is to do a QUAKE/W dynamic analysis to compute the dynamic stresses that the ground will experience during an earthquake. The QUAKE/W *Equivalent Linear* analysis type is used in this case. The required G-reduction function required can be viewed in the data file. The G-reduction function is based on the QUAKE/W built-in estimation procedure. A simple constant 0.02 (2%) damping ratio is used.

The Near field earthquake record data has an interval of $1/100^{\text{th}}$ of a second (0.01). There are consequently 200 data points in the 2-second record. The time integration scheme used in the analysis is based on the time-history record. The computed results are saved to file every fifth time step, and also at the ten highest peaks in the record.

Figure 6 shows the relative lateral displacement along a vertical profile under the center of the dam. This is the motion relative to the specified fixed base. It is this relative motion that creates dynamic shear stresses. Solid body motion does not induce any dynamic shear stresses and is consequently not an issue in this type of analysis. We are only interested in dynamic shear stresses that may lead to plastic yielding and, in turn, permanent deformation.

It is of interest that the largest motion and therefore the largest dynamic shear stresses occur in the soft clay immediately under the dam. The maximum relative lateral movement is only about 0.02 m (20 mm).

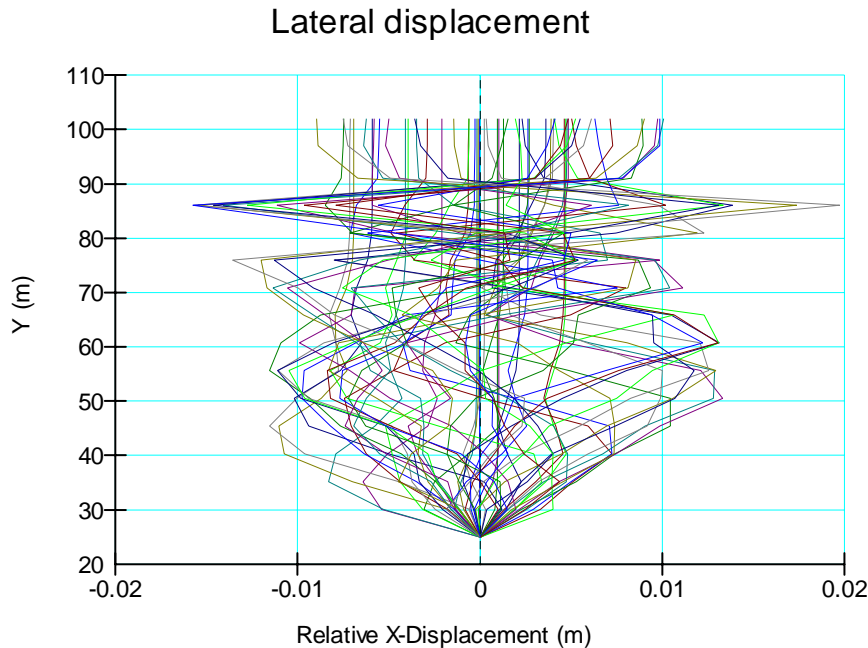


Figure 6 Relative lateral displacements under the dam during the earthquake

It is very important to comprehend that the movements that occur during the earthquake analysis are not related to the permanent deformation. The dynamic motion induces dynamic shear stresses, which may cause some permanent plastic deformations. This is computed in the next analysis.

8 Permanent deformations – Near field

Now that the static and dynamic stresses are known, the information can be used in SIGMA/W to estimate the plastic permanent deformations. This is done with a special *Dynamic Deformation* analysis type in SIGMA/W.

The *Dynamic Deformation* analysis is fundamentally an elastic-plastic stress redistribution analysis. The dynamic stresses are redistributed for each time step that the QUAKE/W results are saved to file.

SIGMA/W computes an incremental load vector based on the stress difference between two time steps. The load vector is computed for each element from:

$$\{\Delta F\} = \int_v [B]^T \{\Delta \sigma\} dv$$

where $\{\Delta \sigma\} = \{\sigma_n\} - \{\sigma_{n-1}\}$ and n is the saved time step.

The incremental load vector is the algebraic difference in the stress states between two successive time steps.

Each load step may produce some elastic strains and some plastic strains. It is the accumulation of the plastic strains and deformations that are a measure of the permanent deformations.

Figure 7 shows the displacement field as a deformed mesh at the end of the 2 seconds of shaking.

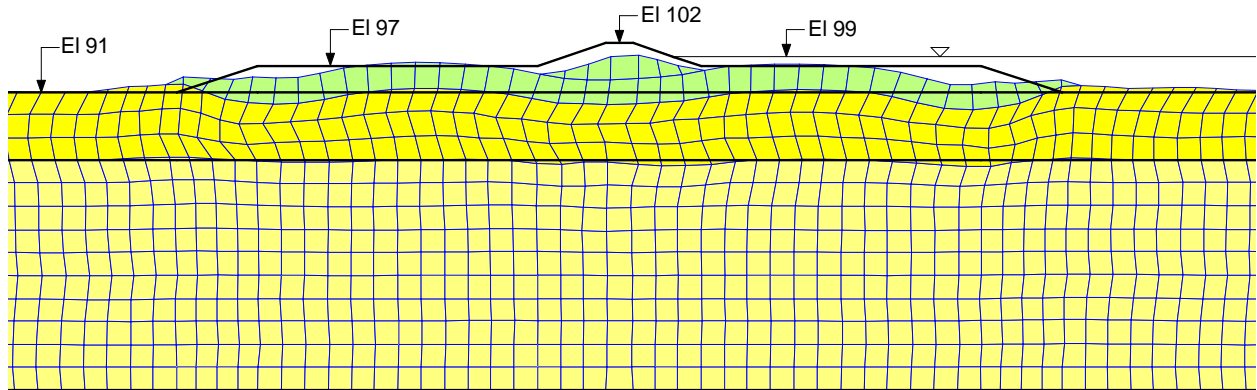


Figure 7 Permanent displacement field as a deformed mesh resulting from the Near-field record (exaggeration x200)

The cumulative vertical settlement at the dam crest is shown in Figure 8. The total amount is only about 0.014 m (14 mm).

It is very important to note that the Initial Stress Conditions for the *Dynamic Deformation* analysis are the static stresses at time zero from the EP stress redistribution – not the last time step of the QUAKE/W shaking analysis.

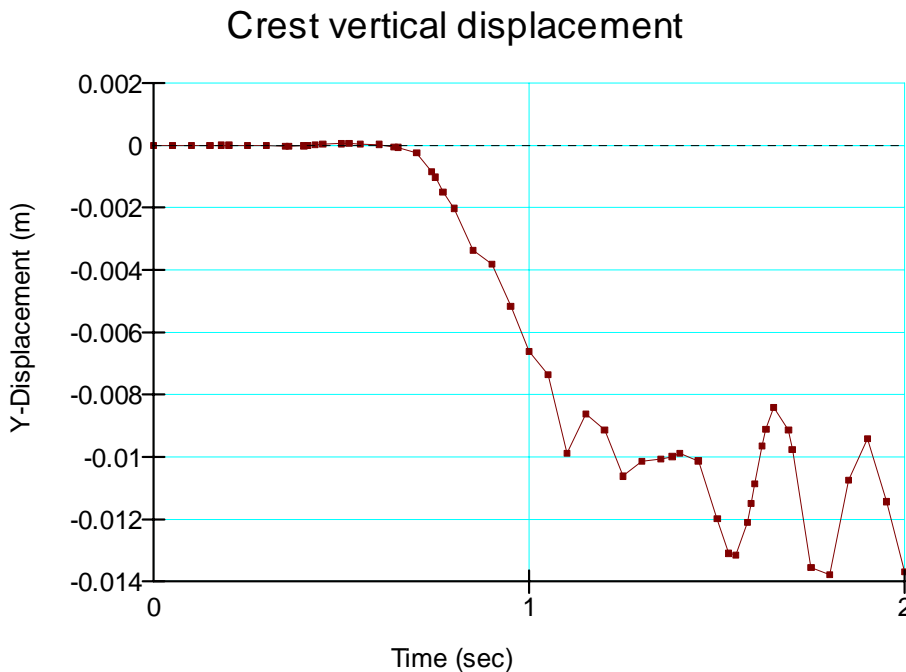


Figure 8 Vertical permanent settlement at the dam crest

Law et al. (2005) computed a permanent displacement for this case of about 40 mm. The reason for the difference between this value and the GeoStudio computed value is not clear. The starting condition, for example, of their analysis is not known from the publication. The stress-redistribution of the initial insitu

conditions results in a vertical crest settlement of about 0.02 m. If we add this to the 0.014 shown in Figure 8, the total is about 0.034 m which is very close the Law et al. reported value.

9 Newmark analysis – Near field

The QUAKE/W results can be used in SLOPE/W to do a Newmark-type of permanent deformation analysis. The variation in safety factors during the Near-field shaking is illustrated in Figure 9. The safety factors move up and down relative to the static condition but never dip below unity (1.0).

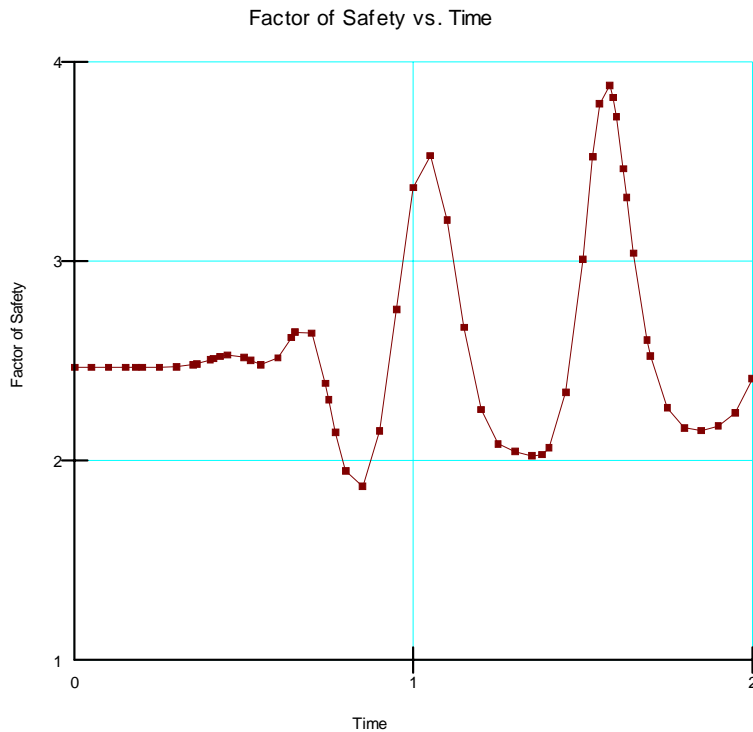


Figure 9 Factors of safety during the Near-field shaking

Since the factors of safety never go below 1.0, a Newmark-type of analysis infers there will be no permanent deformation. This is obviously not the case as indicated by the earlier *Dynamic Deformation* analysis, and is the reason why a Newmark-type of analysis is inappropriate in a case like this where the static factor of safety is relatively high.

10 Permanent deformations – Far field

The above analyses are repeated in this example for the Far-field earthquake record.

The permanent displacement field is illustrated in Figure 10. Of interest is that there is some lateral spreading in both directions in the upper soft clay, but there is also some downstream movement at depth.

The cumulative vertical crests permanent deformation is presented in Figure 11. At the end of the 16 seconds of shaking, the permanent settlement is about 0.05 m (50 mm).

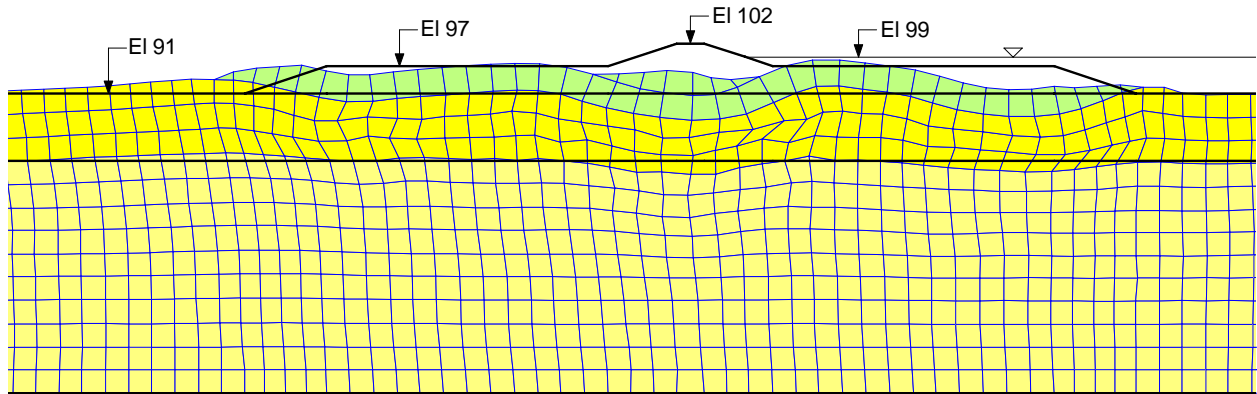


Figure 10 Permanent displacement field as a deformed mesh resulting from the Far-field record (exaggeration x100)

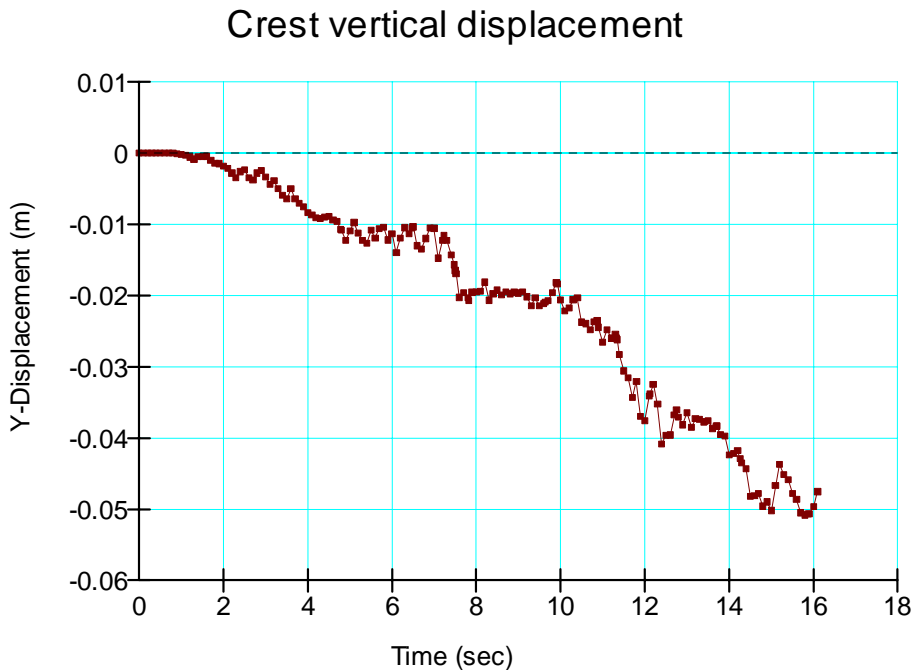


Figure 11 Vertical permanent settlement at the dam crest from the Far-field record

The 50 mm computed settlement again is somewhat less than the 85 mm value computed by Law et al. (2005). However, once again if we add the 0.02 m associated with the initial static stress re-distribution the GeoStudio computed value is reasonably close to the magnitude reported by Law et al. Regardless of the exact details, the two values are remarkably close, considering that they were computed independently using completely different software packages.

The variation in safety factors during the Far-field shaking are shown in Figure 12. Again the safety factors never dip below 1.0, and therefore the Newmark-type of analysis infers there will be no permanent deformation, which is obviously not the case.

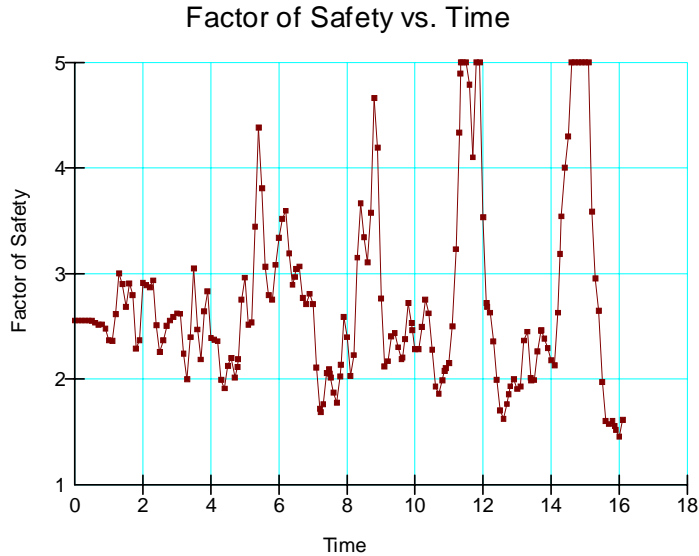


Figure 12 Factors of safety during the Far-field shaking

11 Concluding remarks

This example illustrates how the results from a QUAKE/W dynamic analysis can be used in SIGMA/W to compute the permanent plastic strains and deformations that may occur when an earth structure is subjected to earthquake shaking.

The favorable comparison with a published case history lends credence to fact that the GeoStudio formulation and procedure gives reasonable and acceptable results.

This type of analysis is applicable when the dynamic stresses cause plastic strains, but there is no significant soil strength loss due to the generation of excess pore-pressures or some other detrimental soil strength loss due to the shaking. For a post-earthquake deformation analysis, a one-step Stress Redistribution type of analysis at the end of the shaking would be more appropriate.

From a practical point of view, the GeoStudio analysis is sufficient to conclude that the permanent deformation of this structure when subject to the specified earthquake will likely be in the order of 10's of mm, but not 100's of mm. Or stated another way, the permanent deformations will not be large enough to impede the design function of the structure.

12 References

Law, K.T., Refahi, K., Chan, P., Ko, P., Lam, T., Tang, J. and Hassan, P. (2005). Instantaneous Factors of Safety of Waba Dam during Earthquakes, Conference Proceeding: 58th Canadian Geotechnical Conference, Saskatoon, Saskatchewan, Canada

Law, K.T., Refahi, K., Ko, P., Lam, T., and Hassan, P. (2005). Seismic Deformation of Waba Dam, Conference Proceeding: Canadian Dam Association, Calgary, Alberta Canada.