Waba Dam Deformation

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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.

Background

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-water 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.

Numerical Simulation

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.

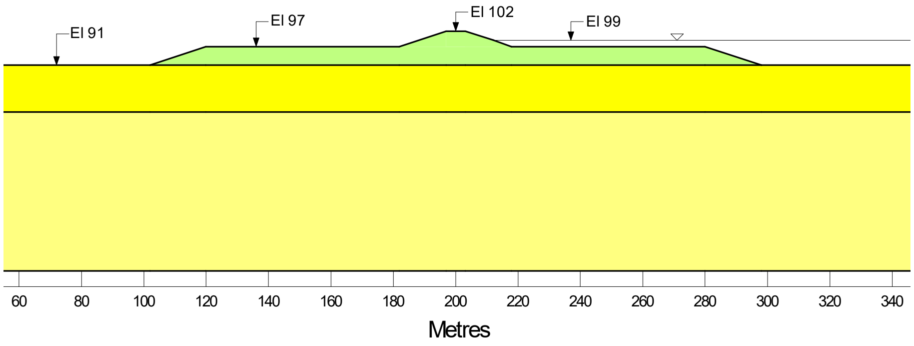


Figure 1. Waba dam cross-section.

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-water 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:

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

Equation 1

where the Poisson's ratio (v)is taken to be 0.45.

Two earthquake records were considered by Law et al. (2005). One was called a 'Near field' record and the other was 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. Only the Far field record is used in this example.

SIGMA/W, QUAKE/W and SLOPE/W are used in the Project (Figure 4). Each of the analyses is discussed as to its purpose.

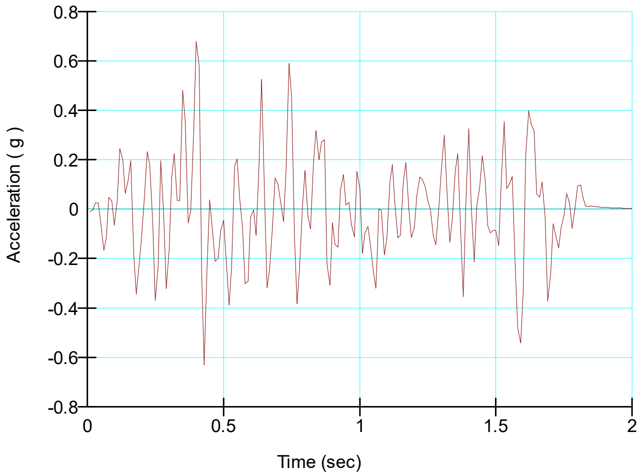


Figure 2. Near field earthquake record.

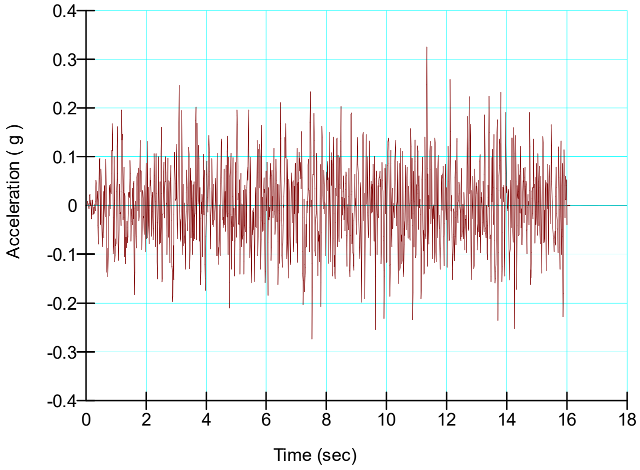
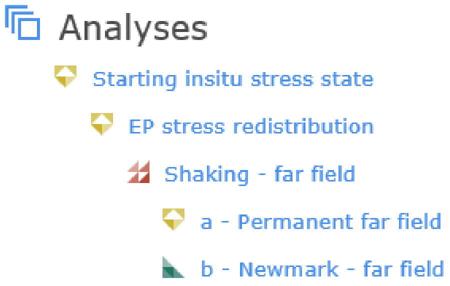


Figure 3. Far field earthquake record.



Analyses

- Starting insitu stress state
  - EP stress redistribution
    - Shaking - far field
      - a - Permanent far field
      - b - Newmark - far field

Figure 4. Waba dam analysis tree.

The first step is to establish the long-term static stress *in situ* 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.

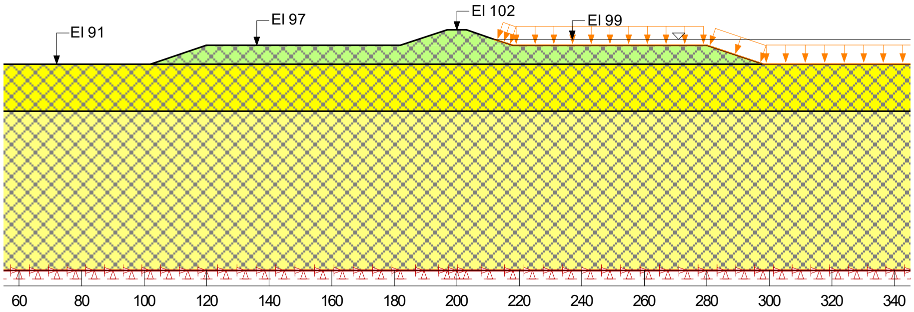


Figure 5. Setup to establish the starting insitu stress state.

The *Insitu* 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 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.

Now that the *in situ* 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.

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:

$$\{\Delta F\} = \int_{v} [B]^{t} \{\Delta\sigma\} dv$$

Equation 1

where $\{\Delta\sigma\} = \{\Delta\sigma_n\} - \{\Delta\sigma_{n-1}\}$ 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.

Results and Discussion

Figure 6 shows the relative lateral displacement along a vertical profile under the center of the dam during the earthquake shaking. 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.

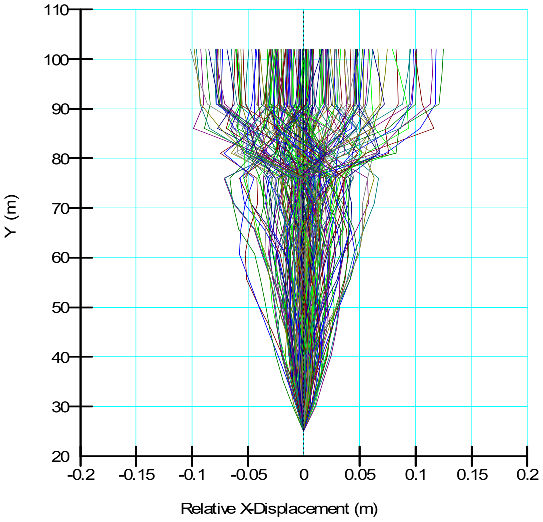


Figure 6. Relative lateral displacements under the dam during the earthquake.

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.

Figure 7 shows the displacement field as a deformed mesh at the 15.9-second mark, and Figure 8 shows the displacement field as vectors.

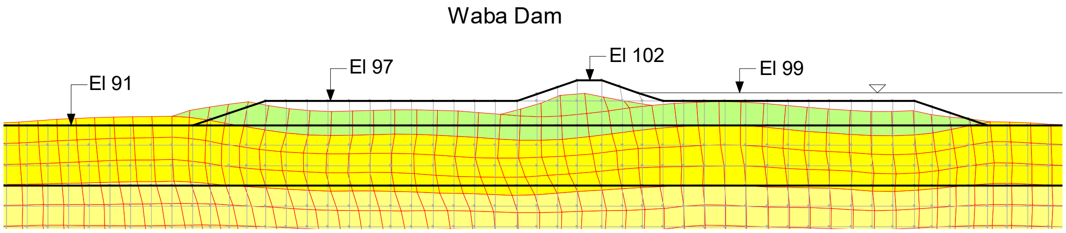


Figure 7. Displacement field as a deformed mesh at the 15.9-sec mark (100x magnification).

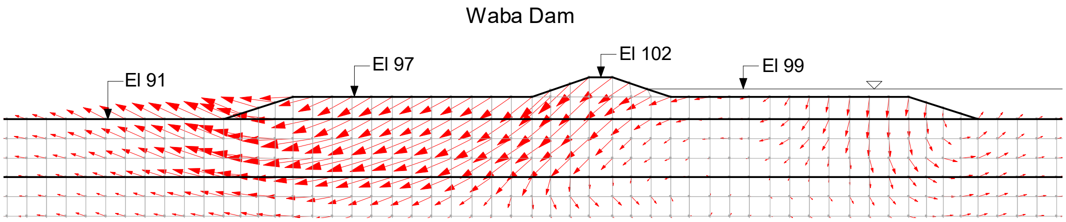


Figure 8. Displacement field as vectors.

The cumulative vertical crests permanent deformation is presented in Figure 9 . At the end of the 16 seconds of shaking, the permanent settlement is about 0.035 m (35 mm).

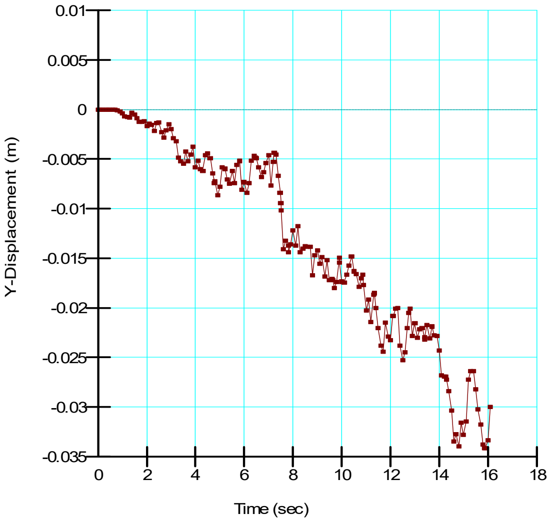


Figure 9. Vertical permanent settlement at the dam crest.

The 35 mm computed settlement again is somewhat less than the 85 mm value computed by Law et al. (2005). The reason for this difference is not clear. It is not clear whether Law et al. did a stress-redistribution before the dynamic analysis as is done here. If we add the 0.035 m associated with the initial static stress re-distribution, the GeoStudio computed value of 70 mm is reasonably close to the magnitude reported by Law et al. Regardless of the exact details, the two values are reasonably 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 10. 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.   This reveals the limitation of a Newmark type of analysis.

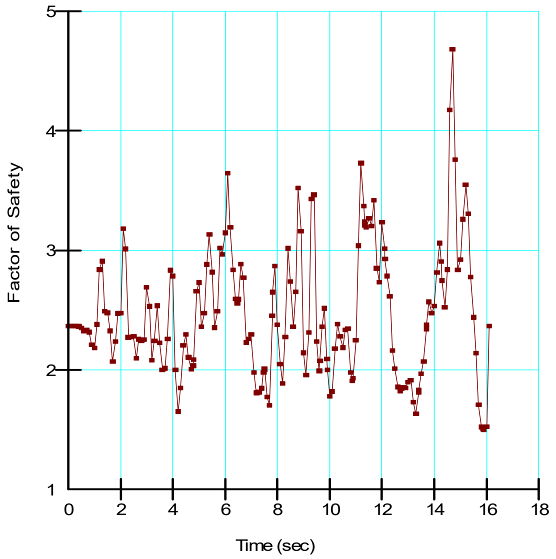


Figure 10. Factors of safety during the Far-field shaking.

Summary and Conclusions

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 the 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-water 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.

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

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