# Dam Construction by Stages

## 1 Introduction

This simple example demonstrates the simulation of staged construction of an embankment on soft ground. The primary purposes of this example are to demonstrate the following functionality:

- Infinite elements for simulating far-field boundaries;
- Undrained strength varying as a function of elevation or y-total stress;
- E-modulus varying as a function of elevation or y-total stress.

## 2 Problem configuration and setup

Figure 1 shows the analysis tree and Figure 2 shows the problem configuration. Notice the infinite elements at the left and right boundaries. The entire construction history is simulated twice: once with the E-modulus and Undrained Strength of the foundation soil varying as a function of elevation and a second time with the variation based on y-total stress. Both the analysis tree and the problem geometry reflect the simulation of the fill placement in 8 successive one-metre lifts. The initial (in situ) stresses are developed prior to the fill placement.

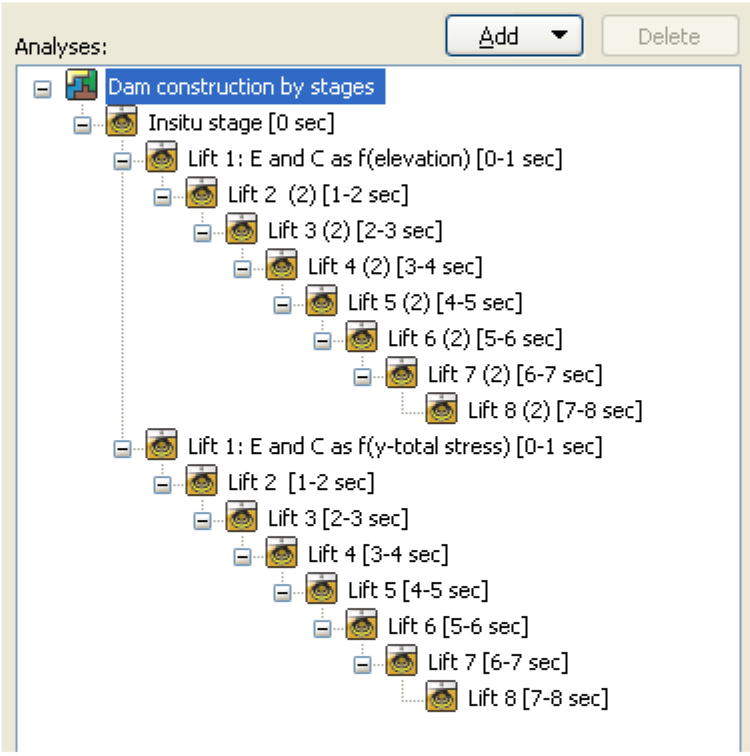


**Figure 1 Analysis-tree diagram**

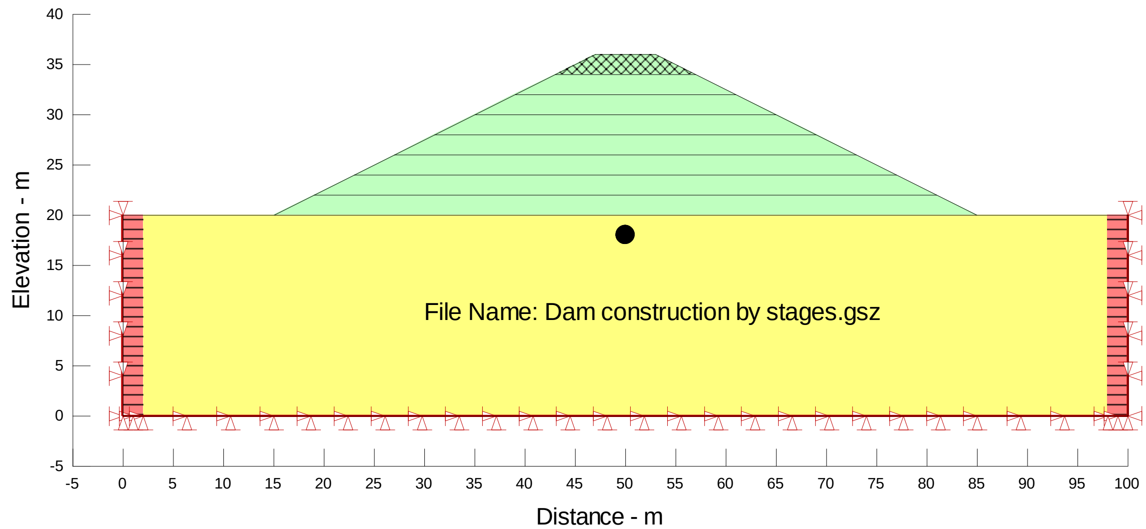


**Figure 2 Problem configuration and setup**

Total stress undrained behavior is assumed for the foundation; that is, the strength is specified as $C_u$ and the *E*-modulus is considered to be a total stress modulus. The embankment material is assumed to be granular soil with a low stiffness.

Figure 3 and Figure 4 show how undrained strength in the foundation soils can be made to vary as a function of elevation and y-total stress, respectively. Notice three things: 1) the undrained strength increases with depth; therefore, the minimum exists at the largest elevation or the smallest y-total stress; 2) the upper two metres of soil have a constant undrained strength of about 40 kPa; and 3) the undrained strength increases at about 20 kPa per metre. The function is specified using data points, so any shape or or rate of change can be accommodated.

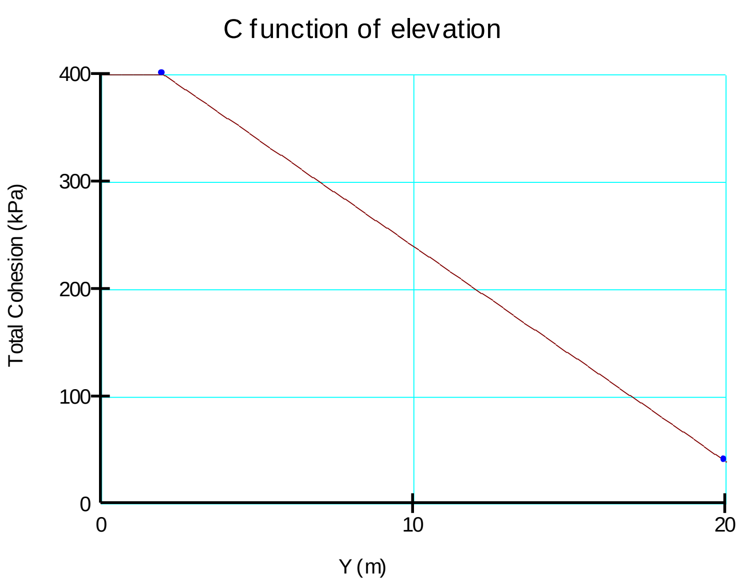


**Figure 3 Undrained strength varying as a function of elevation.**

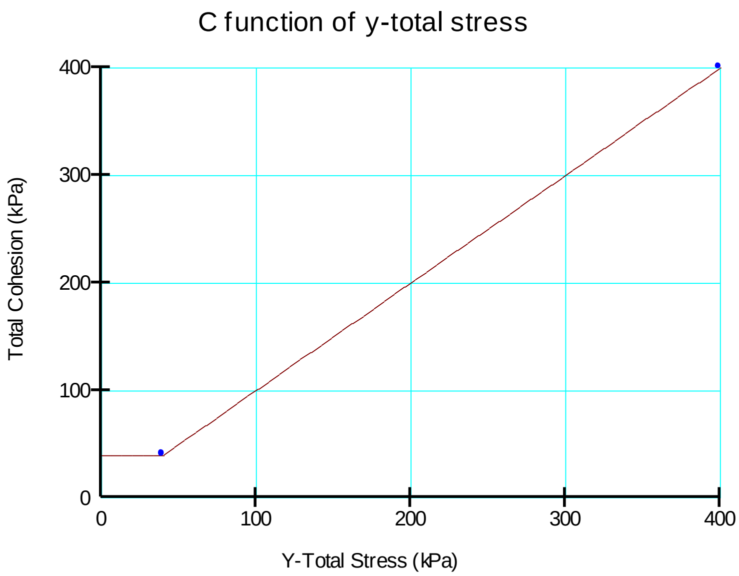


**Figure 4 Undrained strength varying as a function of y-total stress**

As the fill is placed, the total stresses will change; however, the assumption is that the foundation soils respond in an undrained manner; consequently, the undrained shear strength should not vary with loading. This assumption is implicit when the undrained strength is made a function of elevation; however, the user must selection the option Use Initial Stresses when the function is defined using y-total stresses. The undrained strength is then based on the initial insitu stresses and held constant during the embankment loading stages.

The same approach is used with the E-modulus function. The function can also be defined as a function of elevation or y-total stress (Figure 6).

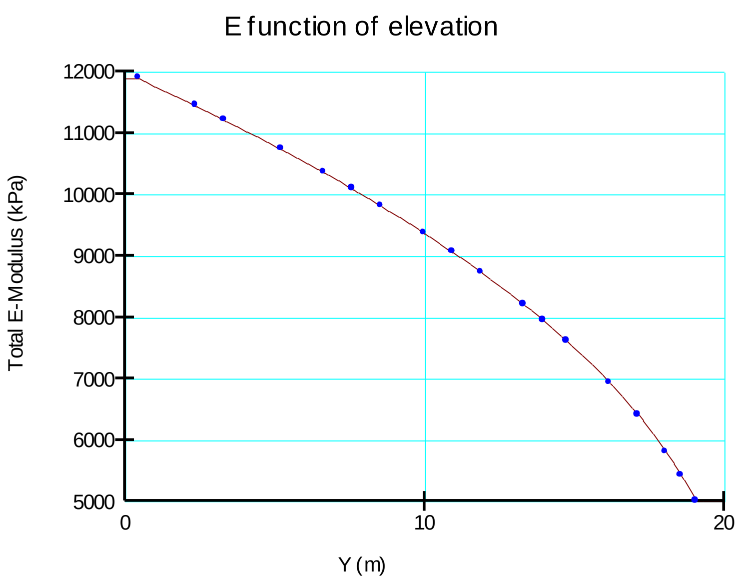


**Figure 5 Foundation E-modulus varying as a function of elevation**

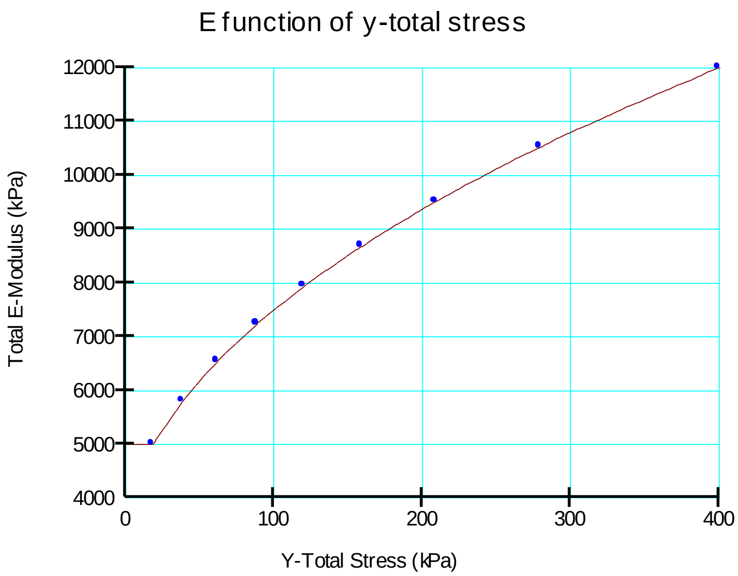


**Figure 6 Foundation E-modulus varying as a function of y-total stress**

The embankment material is treated as being Linear-Elastic. The reason for this is discussed further below.

## 3 Infinite elements

Infinite elements are used at both ends of the problem. This is a very convenient way of extending the far-field boundary without extending the mesh. The best way of thinking about infinite elements in a SIGMA/W analysis, is that they are analogous to a spring-like boundary condition. The boundary is not fixed, but it is also not completely free to move.

The most effective use of infinite elements is to treat them as being a Linear-Elastic material.

## 4 Results and Discussion

The results are presented and discussed only for the analysis completed using the modulus and strength functions defined based on y-total stress.

### *4.1 Material property profiles*

The following graph shows the $C_u$ profile for the foundation for all load steps. The legend has units of seconds (sec), which is equivalent to load step number in this particular case. Notice that the profile is the same for all load steps, as it is intended to simulate the undrained behavior. This is also the case for the initial modulus $E_i$ as shown in Figure 7.

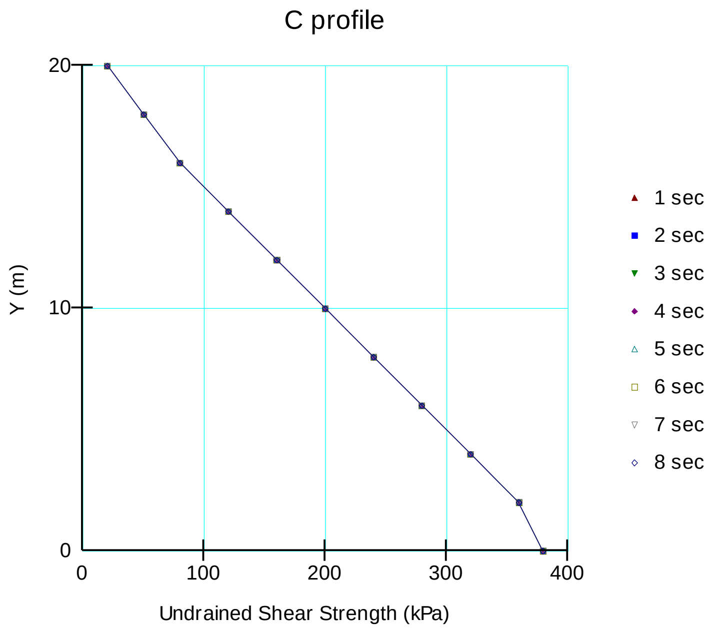


**Figure 7 Undrained strength profile during loading**

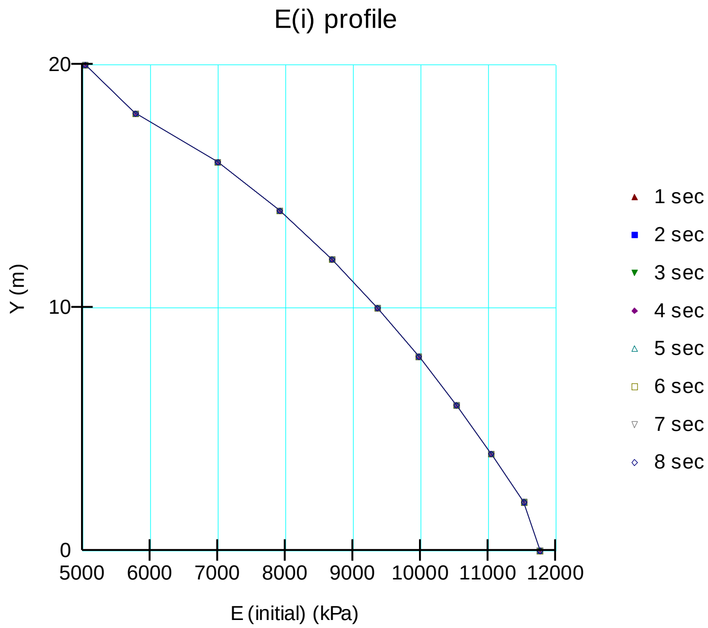


**Figure 8 $E_i$ profile during the embankment loading**

The foundation soil is assigned the Hyperbolic constitutive model, meaning the tangent modulus $E_t$ will change as the shear stresses increase with the loading. This is evident in Figure 9.

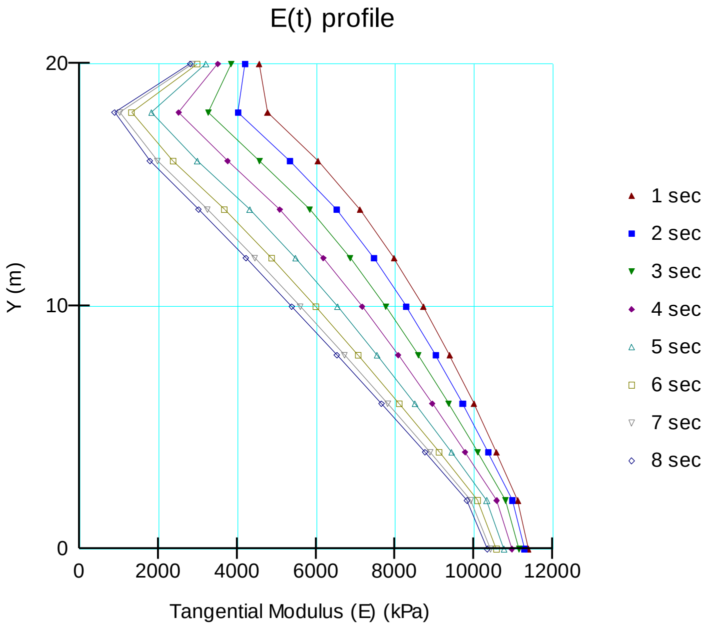


**Figure 9  Tangent modulus $E_t$ profiles for the various loading stages**

## *4.2     Behavior of infinite elements*

Figure 10 shows the response of the infinite elements. Notice how the infinite elements have compressed like a spring, allowing the foundation soil to move to the left.

It is very important to always be mindful of the fact that the edge of the infinite elements is close on the drawing but physical and numerical the outer edge is a long, long way to the left in this diagram.

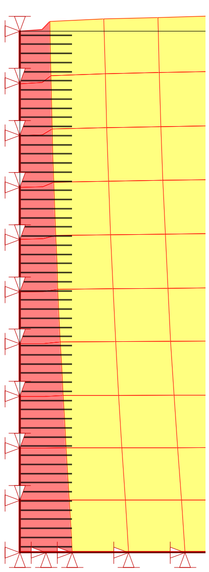

**Figure 10  Response of infinite elements (5X exaggeration)**

## 4.3 Settlements

The vertical settlements along a profile at the center-line of the embankment are shown in Figure 11. Of significance is the response that the largest settlement is not at the dam crest.

Displacement profiles along the original ground surface are presented in Figure 12. Notice how there is settlement under the central part of the embankment, but heave in the toe area and outside the toe. This is also evident in the deformed mesh in Figure 13.

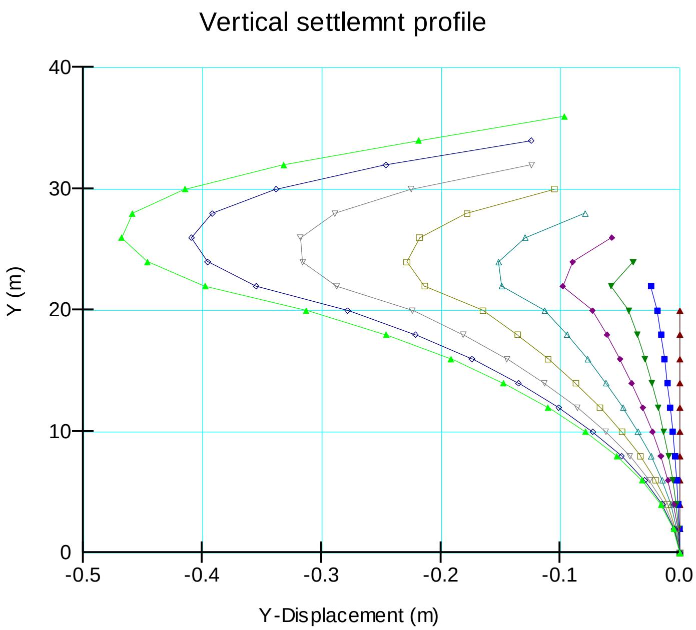


**Figure 11  Vertical settlement profiles along center line of structure**

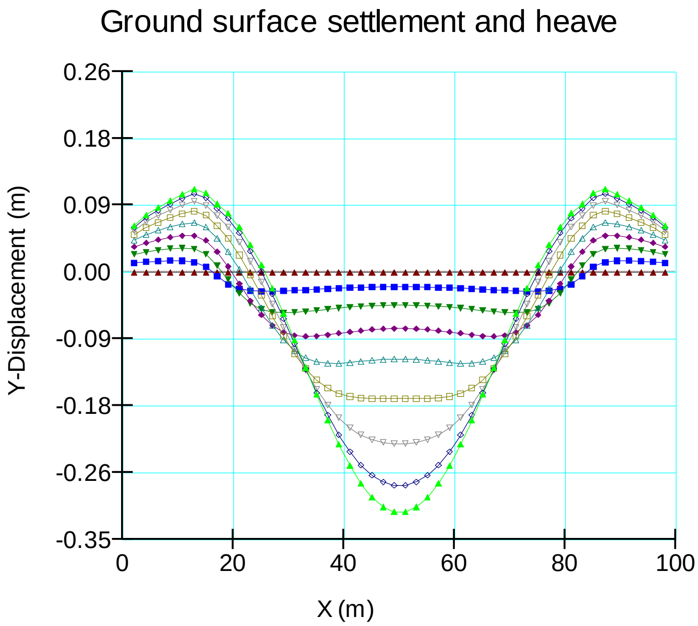


**Figure 12 Settlement along original ground surface**

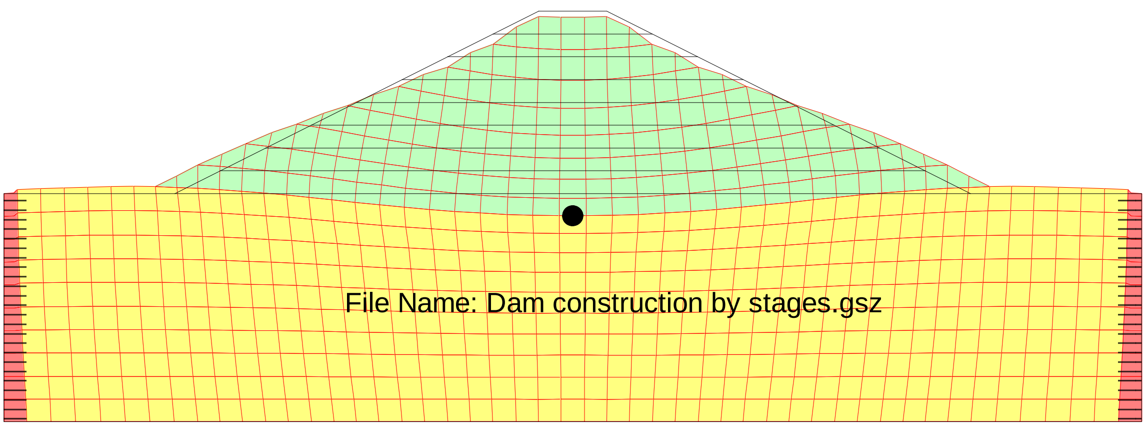


**Figure 13 Deformed mesh showing movements (5X exaggeration)**

## 5 Commentary on modeling fill placement

Numerical simulation of fill placement using the non-linear Hyperbolic model is generally not advisable. The Hyperbolic model can perform poorly when used to simulate embankment fills because of the low confining stresses near the edges of the embankment. The analogy is a sandy material with zero cohesion. For such a situation, the strength approaches zero as the confining stress approaches zero. Similarly, the soil stiffness tends towards zero, making it impossible to obtain a realistic solution to the finite element equations.

A better alternative for modelling the fill is to use the non-linear elastic-plastic Mohr Coulomb model. Alternatively, use the Linear-Elastic model (as was done here) and complete a stress re-distribution analysis (not shown here) if it is deemed essential to ensure there are no overstressed zones in the fill.