12 Embankment Loading on a Cam-Clay Foundation

12.1 Problem Statement

The response of a saturated soil foundation to loading by an embankment is studied in this example. The foundation is 10 meters deep and the groundwater free surface is at the ground level. The embankment is 8 meters wide. The soil behavior corresponds to a Cam-clay material. The initial stress and pore pressure states correspond to equilibrium under gravity with a ratio of horizontal to vertical effective stress of $6/13$. The weight of the embankment is simulated by an applied surcharge, and drainage occurs at the soil surface.

The soil has the following properties.

drained Poisson's ratio (ν)	0.3
soil constant (M)	0.888
slope of normal consolidation line (λ)	0.161
slope of elastic swelling line (κ)	0.062
reference pressure (p'_1)	100.0 Pa
specific volume at reference pressure (v_λ)	2.858
porosity	0.3
dry density (ρ)	2×10^3 kg/m^3

The clay is lightly over-consolidated, and the initial value of the cap pressure, p_c, is equal to 1.6 $\times 10^5$ Pa in the example. (Note that for a normally consolidated soil, the value for p_c is equal to 1.579 $\times 10^5$ Pa at the base of the clay layer, where p = 8.33 $\times 10^4$ Pa and q = 7.0 $\times 10^4$ Pa.) The drained Poisson's ratio of the material is assumed to remain constant during the simulation.

The foundation has a permeability, k, of 10^{-12} (m/s)/(Pa/m). The soil moduli are functions of the mean effective pressure and the soil specific volume, quantities which vary in space and evolve during the simulation. The average value of $K + 4/3G$ stays, however, in the order of 10^6 Pa, or two orders of magnitude lower than the water bulk modulus (K_w is 2 $\times 10^8$ Pa). The diffusivity, c, is thus controlled by the soil material in this example, its magnitude can be estimated from the formula $c = k(K + 4/3G)$, and is on the order of 10^{-6} m^2/s. The time scale for the diffusion process can be estimated using $t_c = L^2/c$, where L is the model height. Using L = 10 m, we have that t_c is on the order of 3 years (approximately 10^8 seconds). Compared to that time, construction of the embankment may be assumed to occur instantaneously. An undrained analysis is first conducted to evaluate the foundation settlement in the short-term after building of the embankment; the long-term response is then monitored after allowing drainage from the soil surface.

12.2 Modeling Procedure

The model, represented in Figure 12.1, takes advantage of half symmetry. The size is 20 meters wide and 10 meters deep. Note that the width of the model is not necessarily large enough to accurately represent an extensive soil layer; the model is intended for illustrative purposes only. The mechanical boundary conditions correspond to roller boundaries along the symmetry line and the far boundary of the model, and to fixed displacements in the x- and y-direction at the model base. The maximum bulk modulus of the clay (**bulk**) is set to 5×10^6 Pa, a value that is approximately twice the initial value of the actual bulk modulus (**bulk_current**) at the bottom of the clay layer.

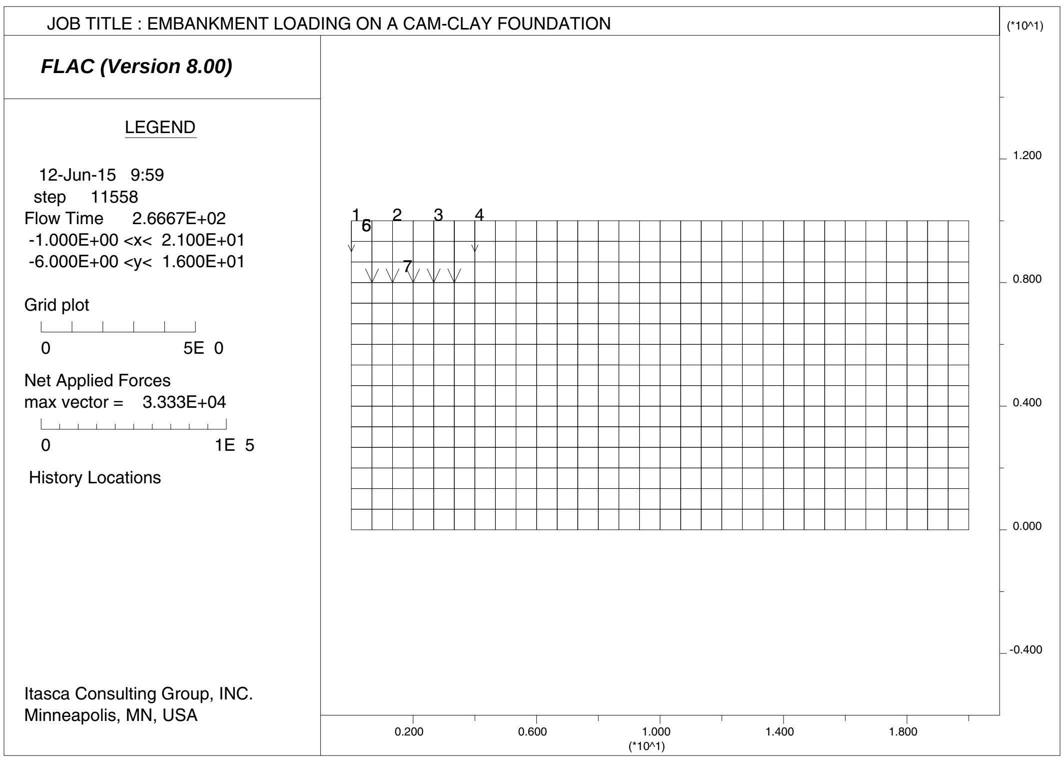

Figure 12.1 Model geometry

The first foundation settlement stage of the simulation corresponds to the short time response of the system in which no flow is assumed to take place. The command **SET flow off** is specified. Loading by the embankment is simulated by progressive application of a pressure of 50 kPa on a 4 meter section of the model top boundary. The `ramp` *FISH* function is used to apply the load gradually. This procedure avoids overshoots related to transient loading. Once the full load is attained, the model is cycled to equilibrium. During this stage, pore pressures develop as a result of volumetric deformations, but do not dissipate.

In the second stage, fluid flow is allowed to develop by issuing the command **SET flow on**. Water then drains through the top of the model where the pore pressure is fixed at zero, and additional settlement takes place under the embankment. The **SOLVE auto on** command, used to perform the coupled simulation, requires parameters that determine the accuracy of the solution. These parameters may need to be different if different properties or model conditions are used. Refer to Section 1.8.6 in **Fluid-Mechanical Interaction** for a discussion on these topics.

Stresses, pore pressures and vertical displacements are monitored during the calculation. The project file for this problem is "embankment.prj".

12.3 Results and Discussion

Displacement vectors, vertical displacement contours, the pore pressure distribution and the plastic state at the end of the undrained and drained numerical simulations are presented in Figures 12.2 to 12.9. The vertical displacement histories in Figure 12.10, recorded at four monitoring points (locations 2, 3, 4 and 5 in Figure 12.1), indicate that the maximum settlement under the embankment increases from approximately 0.16 cm to 0.20 cm as a result of drainage. Note that the displacement vectors in Figure 12.3, and vertical displacement contours in Figure 12.5, correspond to the combined undrained and drained displacements.

In Figure 12.11, the graph of pore-pressure evolution at two monitoring points (locations 8 and 9 in Figure 12.1) confirms that a steady-state flow has been reached by the end of the drained simulation.

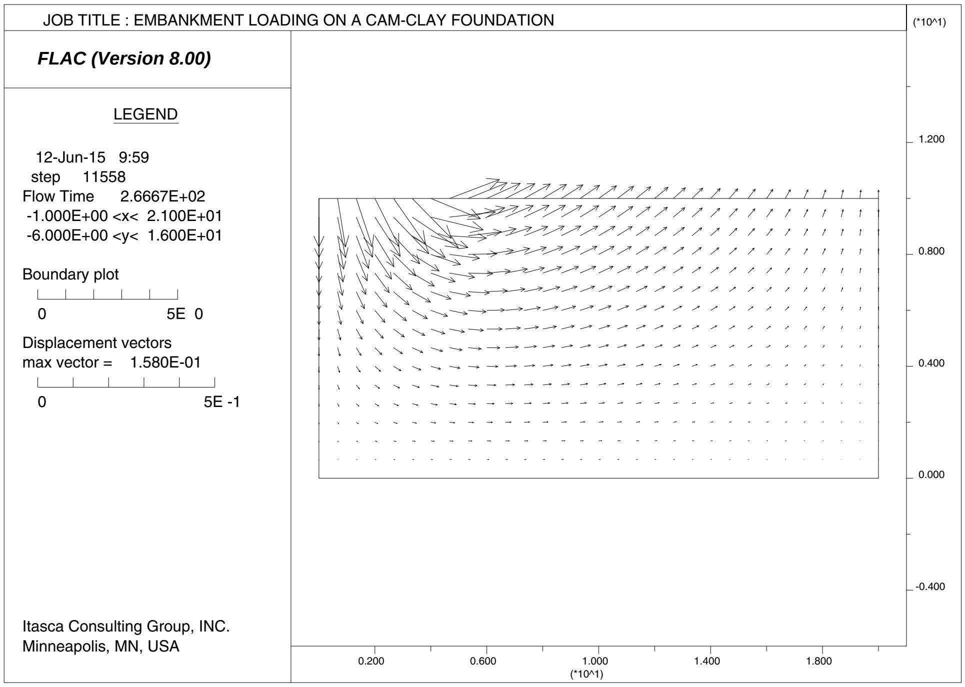

Figure 12.2 Displacement vectors – undrained response

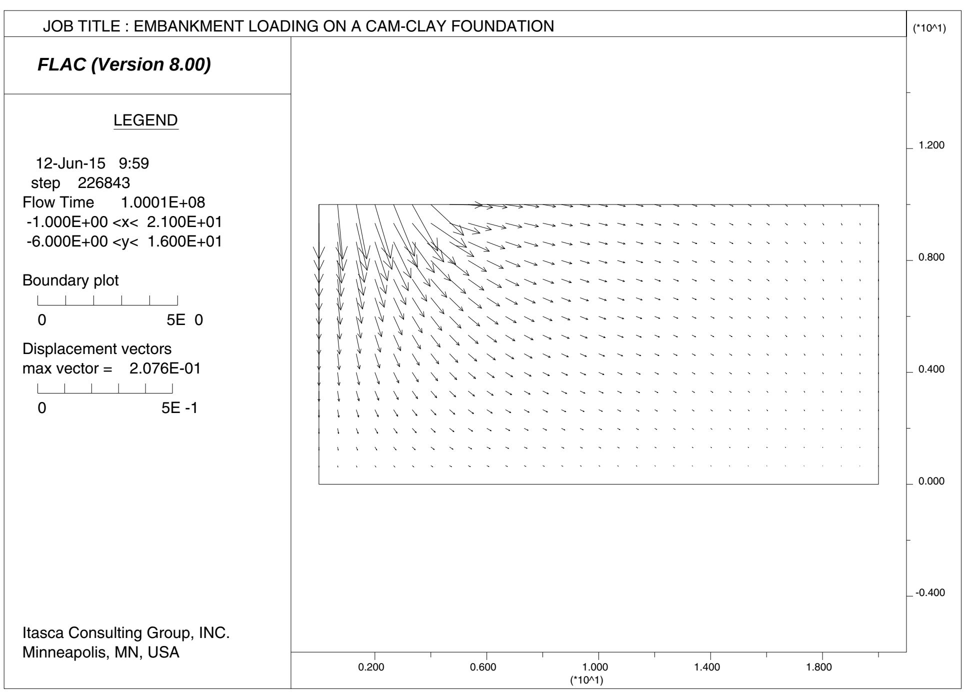

Figure 12.3 Displacement vectors – end of drained simulation

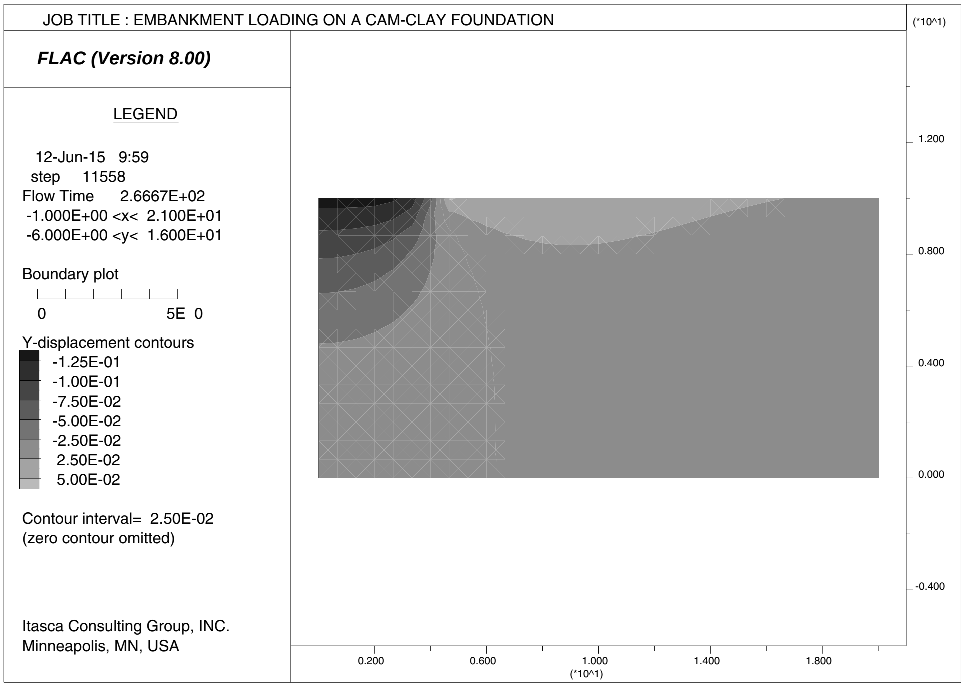

Figure 12.4 Vertical displacement contours – undrained response

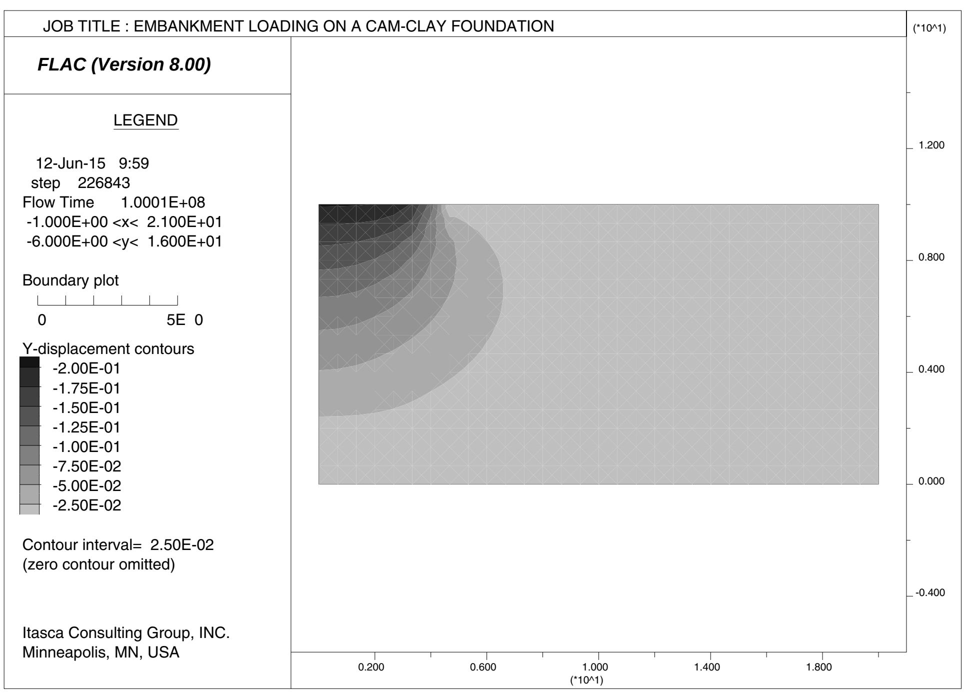

Figure 12.5 Vertical displacement contours – end of drained simulation

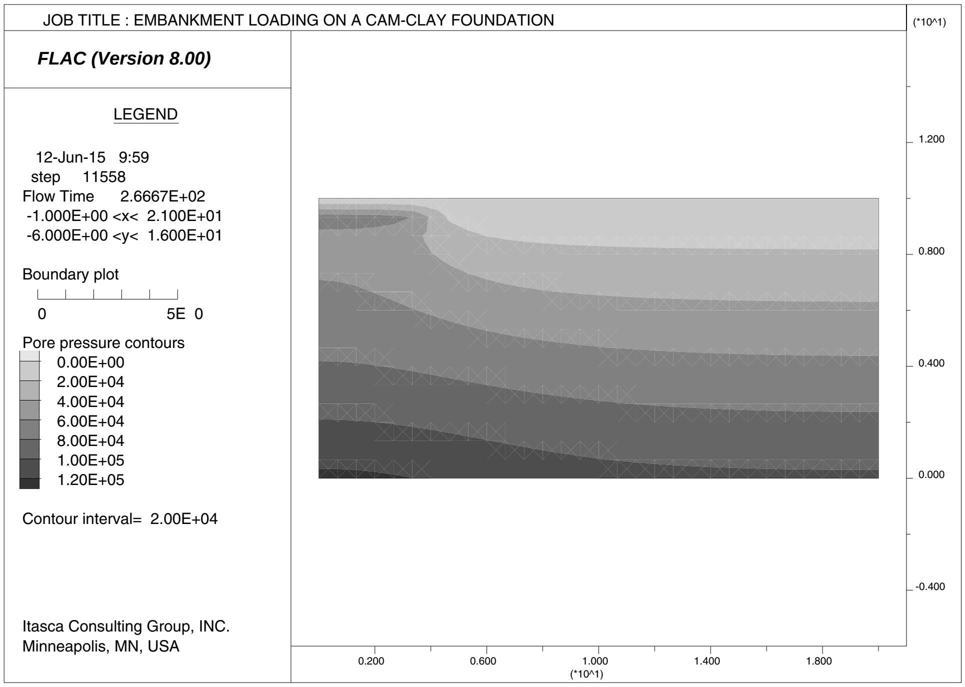

Figure 12.6 Pore pressure contours – undrained response

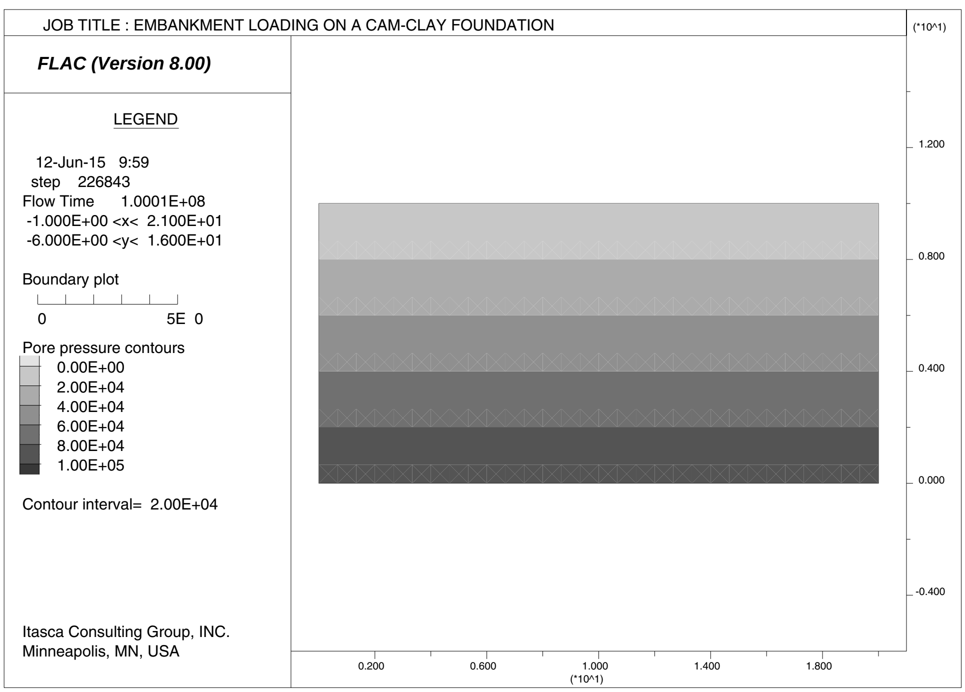

Figure 12.7 Pore pressure contours – drained response

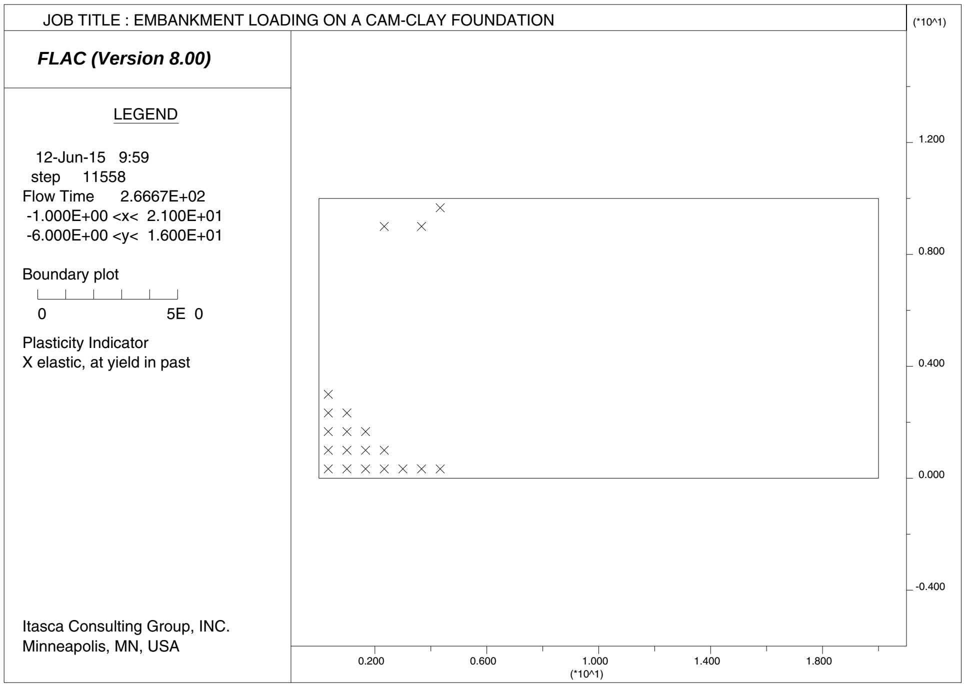

Figure 12.8 Plastic state – undrained response

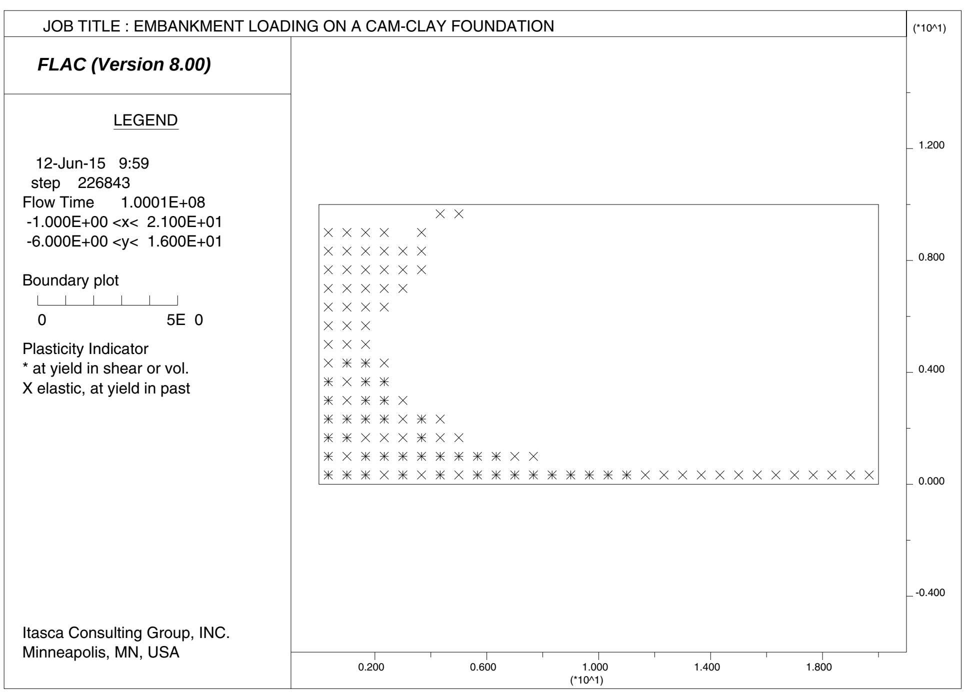

Figure 12.9 Plastic state – drained response

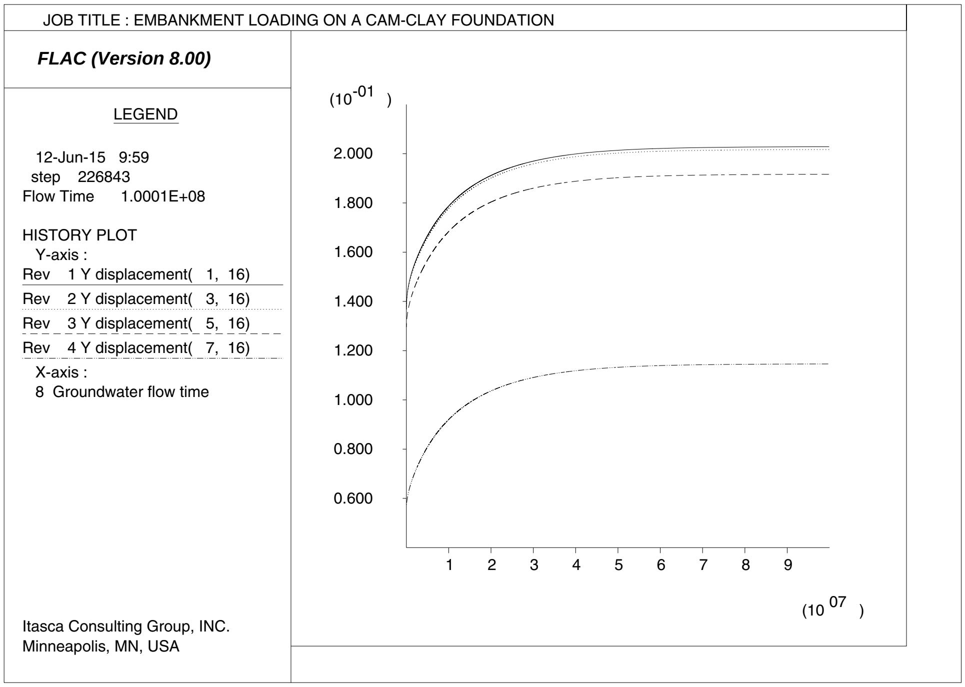

Figure 12.10 Vertical displacement histories – drained response

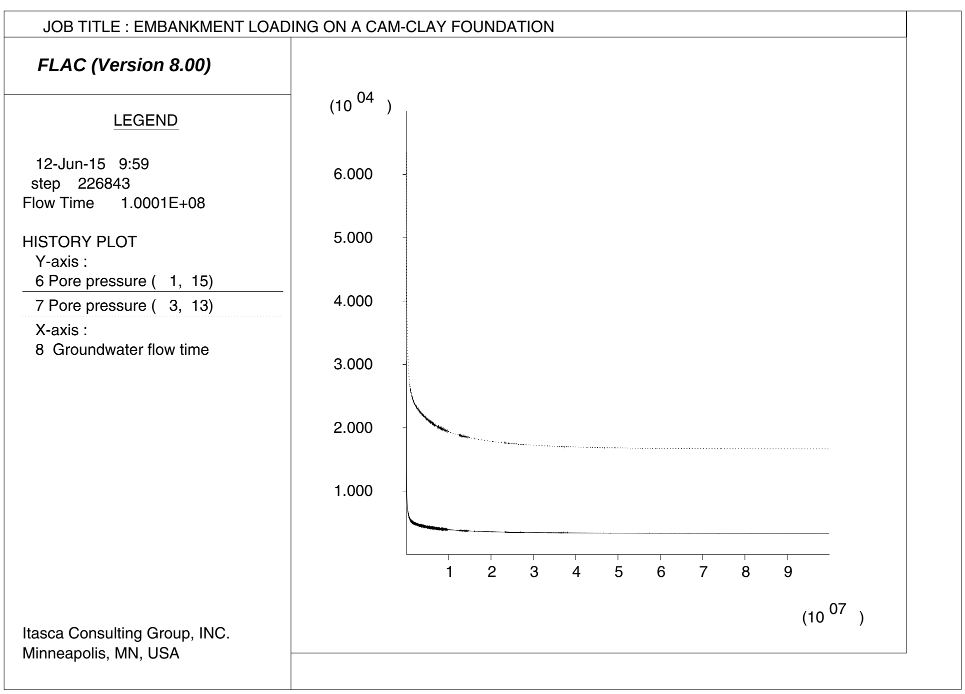

Figure 12.11 Pore pressure histories – drained response