CUSTOMER SUPPORT NOTE

Geotechnical modelling methods for short term, long term and full consolidation behaviour

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This support note is issued as a guideline only.

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1. Introduction

When carrying out a full non-linear, geotechnical analysis using LUSAS where the actual ground itself is discretised into finite elements (i.e. Winkler Springs are not used), it is important to establish whether short term, long term or full consolidation behaviour is required. This will initially depend on the type of soil present in the model and more specifically, the permeability of the material. The permeability will control how quickly excess pore pressures set up in the soil due to excavation/construction will come to equilibrium.

Sandy or gravelly soils with relatively high permeabilities will enable excess pore pressures to dissipate almost immediately and so a “drained” or long-term analysis will be necessary. Soils with a large clay content and therefore a low permeability however will mean that excess pore pressures dissipate much more slowly, often taking many years to reach equilibrium. In this case it is important to establish whether it is the short term behaviour which is required (immediately post-construction) or the long-term behaviour (once full dissipation of excess pore pressures has taken place). This will often be dependent on the type of analysis in question and which condition is the more critical in terms of stability. Cuttings and excavations will be more stable in the short term when negative excess pore pressures are present while embankments and foundation type problems will be more stable in the long term once excess pore pressures have been completely dissipated.

LUSAS also has the capability to model the full consolidation sequence using “Two-Phase” plane strain elements and so the excess pore pressure dissipation with time can be reproduced simulating the change from short term to long term behaviour. This type of model may be necessary when the engineer requires the length of time taken to establish equilibrium conditions.

This support note will describe how each of these types of analysis should be undertaken using the LUSAS finite element software.

2. Description

2.1 Effective stress

The deformability and strength of soil depends on the effective stress present, NOT the total stress. The effective stress is the difference between the applied external total loading stress, σ and the pore water pressure, u. Therefore when considering the type of analysis required for low permeability soil types such as clay, consideration should be given to the magnitude of effective stresses present within the soil both in the short term and long term conditions.

Excavation of a low permeability soil will give rise to a reduction in pore pressure as well as total stress and therefore the changes in effective stresses will be minimal. As dissipation of excess pore pressures subsequently takes place over time, pore water pressures within the soil will increase and therefore the effective stress will decrease, leading to a reduction in soil strength. In this case it can be seen that the long-term condition is the more critical as the effective stresses within the soil will be at their lowest values.

Construction, on the other hand will give rise to positive excess pore pressures within the soil and subsequent dissipation will lead to an increase in effective stress and strength making the short term condition the more critical. A long term analysis may also be necessary in this case however if the final long-term displacements of the structure are required.

2.2 Initial stresses

The initial, in situ stresses existing in the ground should be entered in the very first loadcase. Variations can be used to represent a varying stress profile with depth. It is important that stresses in all three (X, Y and Z) directions are included for plane strain as well as 3-dimensional analyses. Stress profiles should be entered such that the vertical stress profile balances the gravity load acting from the acceleration due to gravity and the material density. There should be minimal displacements produced in the in situ loadcase.

When carrying out a short-term or consolidation analysis with two-phase elements the initial pore pressure profile within the ground is ignored and therefore generated pressures are always *excess* pore pressures, i.e. pressures above or below the initial pressure profile. Full consolidation will once more give rise to zero pore pressures indicating that all excess pore pressures have dissipated.

2.3 Material model

All geotechnical analyses should make use of a non-linear material model to represent the behaviour of soil as only very small strains are necessary in order to overcome the yield stress and induce plasticity. In general an "elastic, perfectly-plastic" soil model is recommended such as the Mohr-Coulomb failure criteria (Model 65). A more advanced soil model known as Cam clay is due for implementation into the LUSAS software in Version 14.

The Mohr-Coulomb material model can be used for both short term and long term analyses using effective stress as well as total stress soil parameters.

2.4 Long-term, drained solutions

When carrying out drained, long-term solutions, effective stress soil strength and stiffness parameters must be used with the Mohr-Coulomb material model, comprising:

1. Young's modulus, E'
2. Poisson's ratio, ν'
3. Cohesion, c'
4. Angle of friction, ϕ'
5. Angle of dilation, ψ'

Analyses of this type do not consider any generation of excess pore pressures.

2.5 Short-term, undrained solutions

Short term solutions can be carried out as either a total stress analysis using undrained strength and stiffness parameters or as an effective stress analysis using drained parameters together with two-phase finite elements. The latter method will predict the magnitude of excess pore pressures that are induced within the soil due to the construction sequences involved. At present only plane strain problems can be analysed with two-phase elements. Additional material properties are required for two phase elements, namely the bulk modulus of water, the unit weight of water, and the porosity and permeability of the soil continuum.

2.5.1 Total stress analyses

Short-term total stress analyses will require the following undrained, strength and stiffness material parameters to be used with the Mohr-Coulomb material:

1. Young's modulus, E_u
2. Poisson's ratio, $\nu_u = 0.5$
3. Undrained shear strength, C_u
4. Angle of friction, $\phi_u = 0$
5. Angle of dilation, $\psi_u = 0$

Although a value of 0.5 is required for Poisson's ratio to simulate the fact that no volume changes are permitted for undrained, total stress solutions, it is not possible; to enter a value of exactly 0.5 as this will give rise to an infinite bulk modulus. For this reason a value of 0.495 is often used. The angle of friction must always be zero hence analyses of this type are often referred to as "phi = 0" analyses.

Although excess pore pressures will be generated in the short-term condition, they are not calculated in analyses of this type.

2.5.2 Effective stress analyses

Short-term effective stress analyses with two-phase finite elements will require the following drained strength and stiffness material parameters together with additional parameters describing the soil/fluid interaction:

1. Young's modulus, E'
2. Poisson's ratio, ν'
3. Cohesion, c'
4. Angle of friction, ϕ'
5. Angle of dilation, ψ'
6. Bulk modulus of solid particles, K_s
7. Bulk modulus of fluid phase, K_w
8. Porosity, n
9. Unit weight of fluid phase, γ_w
10. Permeability, (k_x, k_y, k_z)

The "equivalent" bulk modulus, K_e of the soil particle/fluid material is derived internally from the supplied values of K_s and K_w by the following relationship:

$$\boxed{\frac{1}{K_e} = \frac{n}{K_w} + \frac{(1-n)}{K_s}}$$

As the bulk modulus of the solid particles, K_s is usually much higher than the bulk modulus of the fluid phase, K_w then:

$$\boxed{\frac{1}{K_e} \approx \frac{n}{K_w}}$$

This type of analysis will predict the generation of excess pore pressures within the soil.

2.6 Full consolidation modelling

The same effective stress input soil parameters used for undrained solutions with excess pore pressure predictions are used for consolidation type problems where the dissipation of these pore pressures are also considered. The "Time domain" option must be switched on in the nonlinear control dialog and set to "Consolidation". The Initial Time Step and Total Response Time must also be set depending on the units of time being used. The analysis will then be carried out as a coupled time-marching solution.

3. Examples

The following examples use two linear, elastic materials to represent a standard silty clay soil upon which an embankment is constructed. The soils should ideally be modelled using a non-linear material; elastic properties have been used in the examples in order to speed up the analysis times.

3.1 Long-term drained analysis

[LUSAS model: embankment_drained.mdl]

This example uses drained, effective stress parameters to model the long term settlement of the embankment. Standard plane strain elements have been used throughout and a maximum displacement of 141mm is produced directly beneath the centre of the embankment as shown in Figure 1.

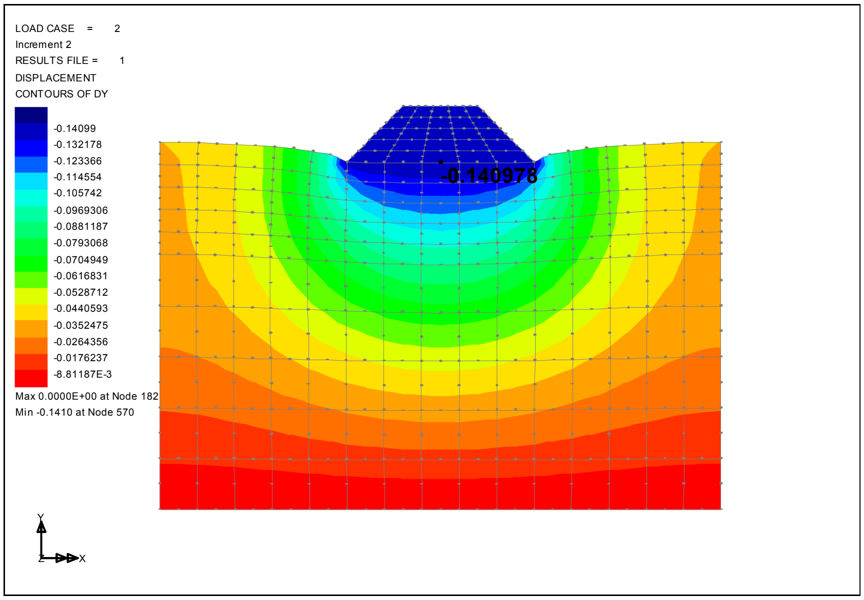

Figure 1. Vertical displacements for long-term drained solution

3.2 Short-term undrained analysis (total stress method)

[LUSAS model: embankment_undrained_total.mdl]

This example uses undrained, total stress parameters to model the short term settlement of the embankment. Standard plane strain elements have been used throughout and a maximum displacement of 37mm is produced directly beneath the centre of the embankment as shown in Figure 2.

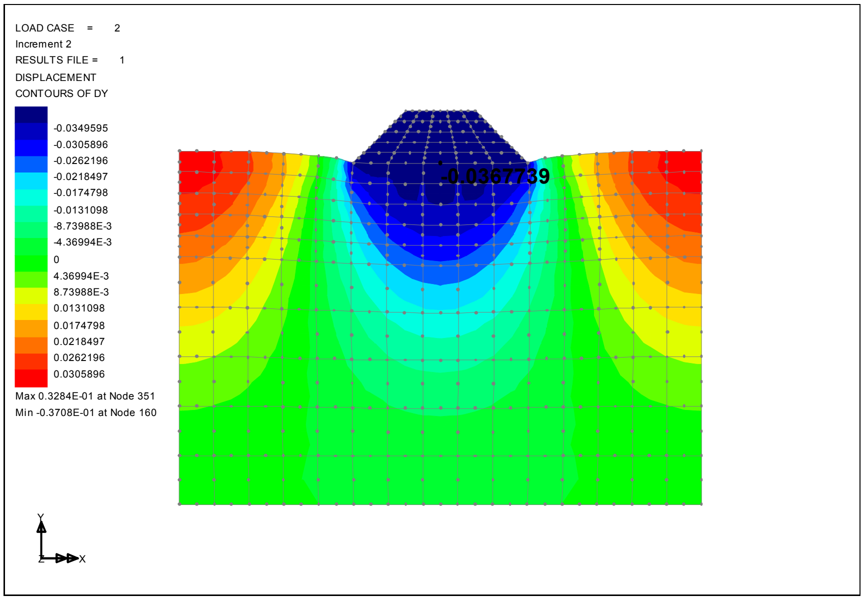

Figure 2. Vertical displacements for short-term undrained solution (total stress)

3.3 Short-term undrained analysis (effective stress method)

[LUSAS model: embankment_undrained_effective.mdl]

This example uses drained, effective stress parameters together with two phase material properties to model the short-term solution. Two phase plane strain elements have been used for the loaded soil while standard plane strain elements have been used for the embankment. A maximum displacement of 40mm is produced directly beneath the centre of the embankment as shown in Figure 3. This result is very similar to the undrained total stress analysis as expected. As two-phase plane strain elements have been used contours of the excess pore pressures generated in the soil due to the placement of the embankment are also calculated as shown in Figure 4.

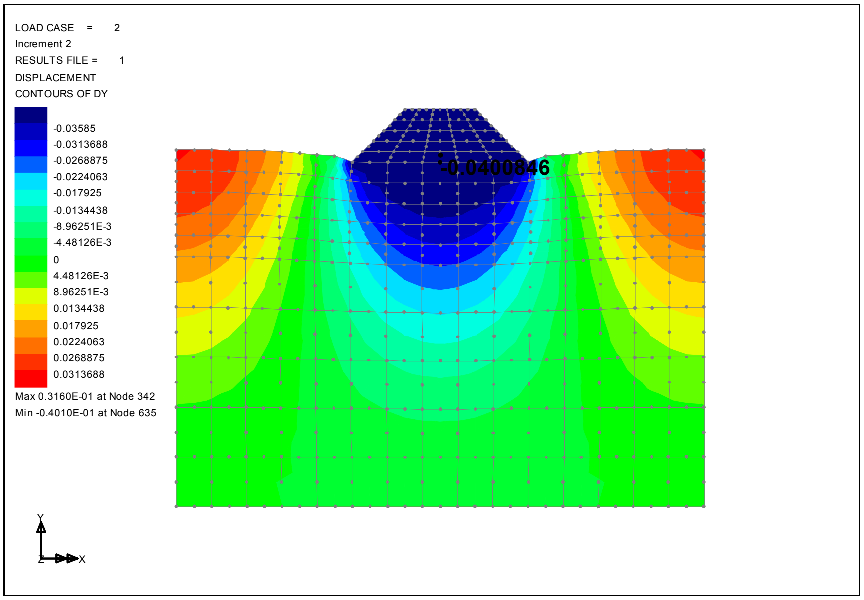

Figure 3. Vertical displacements for short-term undrained solution (effective stress)

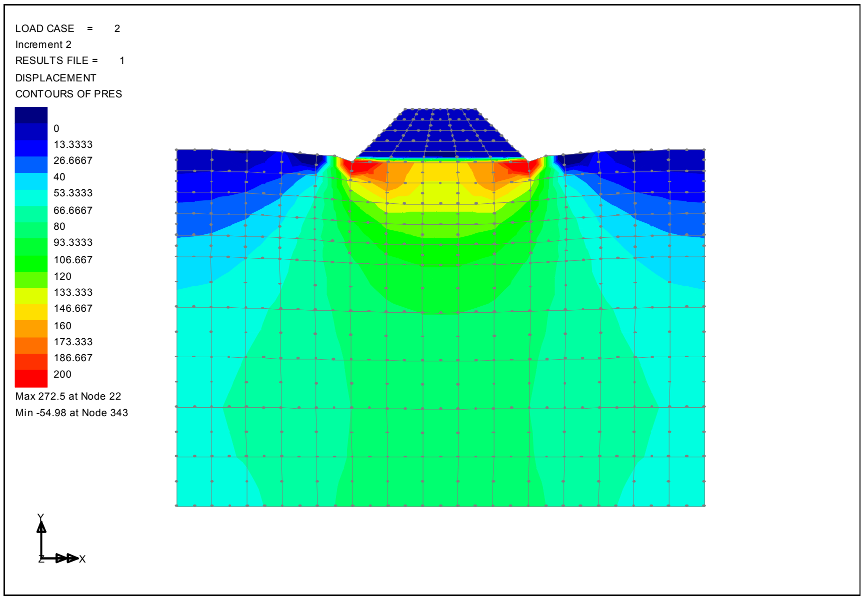

Figure 4: Excess pore pressures for short-term undrained solution (effective stress)

3.4 Consolidation analysis

[LUSAS model: embankment_consolidation.mdl]

This example uses drained, effective stress parameters together with two phase material properties to model the complete time-history solution from the short-term to the long-term in a consolidation analysis. Two phase plane strain elements have been used for the loaded soil while standard plane strain elements have been used for the embankment. Drainage is permitted from the top surface beneath the embankment only. At time T=0 the solution can be compared to the two undrained solutions above and at time T= ∞ with the drained solution. Figure 5 shows that the maximum displacement beneath the embankment at T=0 is 38mm (again in agreement with the two undrained solutions) and Figure 6 shows the excess pore pressures generated which again are in agreement with the undrained effective stress solution. Figure 7 shows the maximum displacement beneath the embankment at T= ∞ which is in excellent agreement with the long-term drained solution.

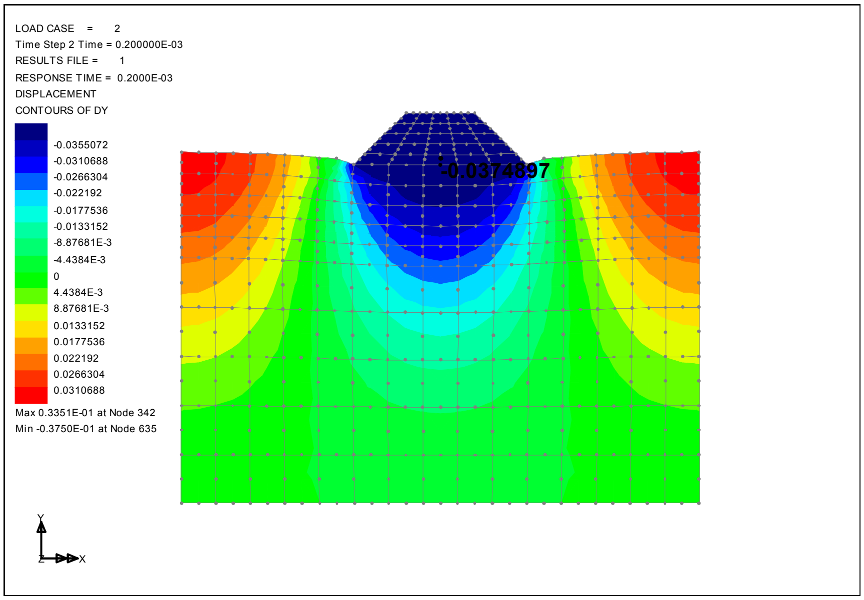

Figure 5: Vertical displacements for consolidation solution at T=0

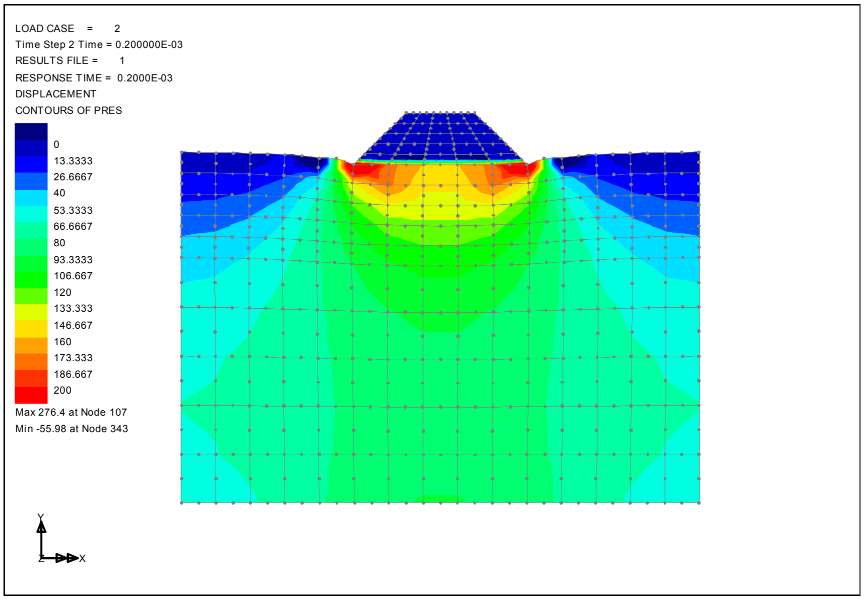

Figure 6: Excess pore pressures for consolidation solution at T=0

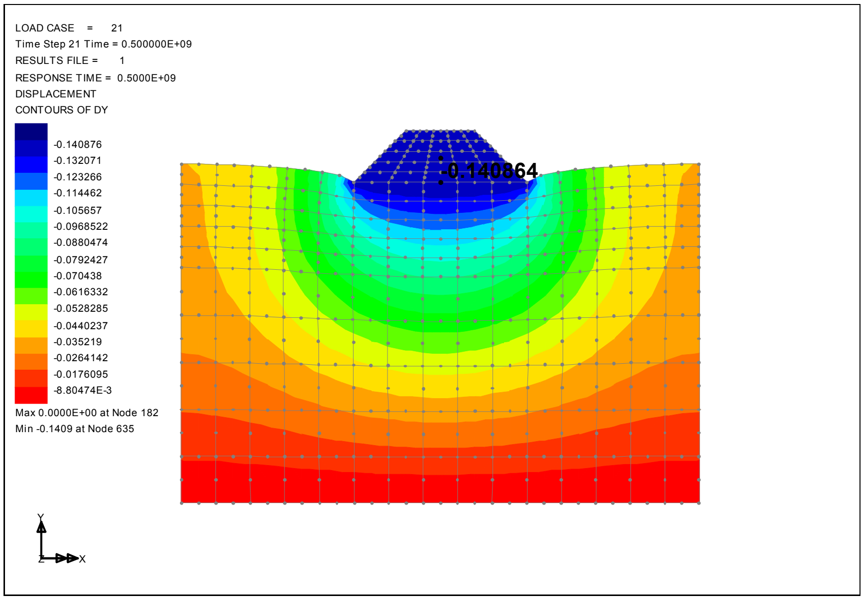

Figure 7: Vertical displacements for consolidation solution at T=∞

3.5 Consolidation analysis of an excavation

[LUSAS model: excavation_consolidation.mdl]

A similar consolidation example has been created for excavation rather than construction. In this case an excavation is carried out in the same soil deposit as the construction examples above. In this case negative excess pore pressures are produced giving rise to suction and water is drawn in from the outside world. This has been permitted at the top boundary of the model only and the excavated region is assumed to be kept clear of free standing water. An excess pore pressure profile on a deformed mesh at time T=0 is shown in Figure 8 and vertical displacement contours at time T=∞ are shown in Figure 9.

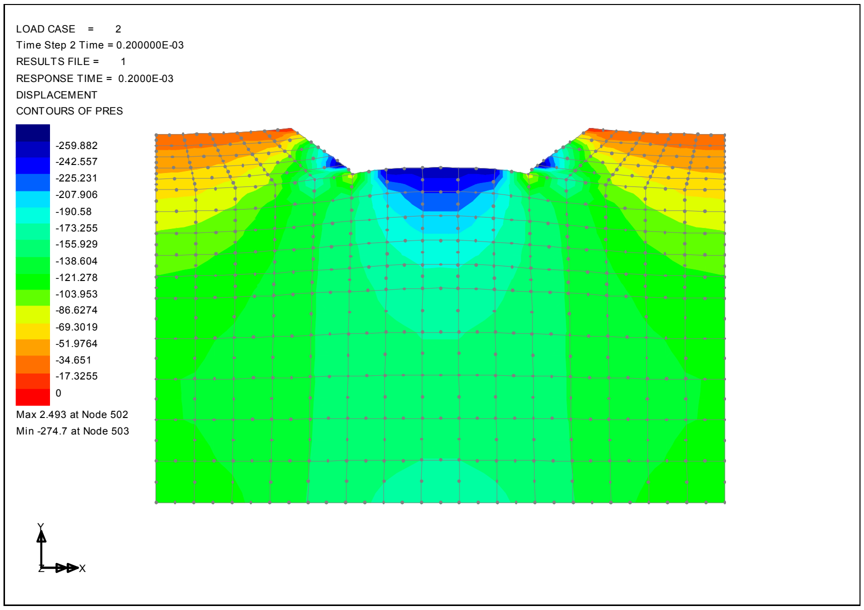

Figure 8: Excess pore pressures for consolidation solution at T=0

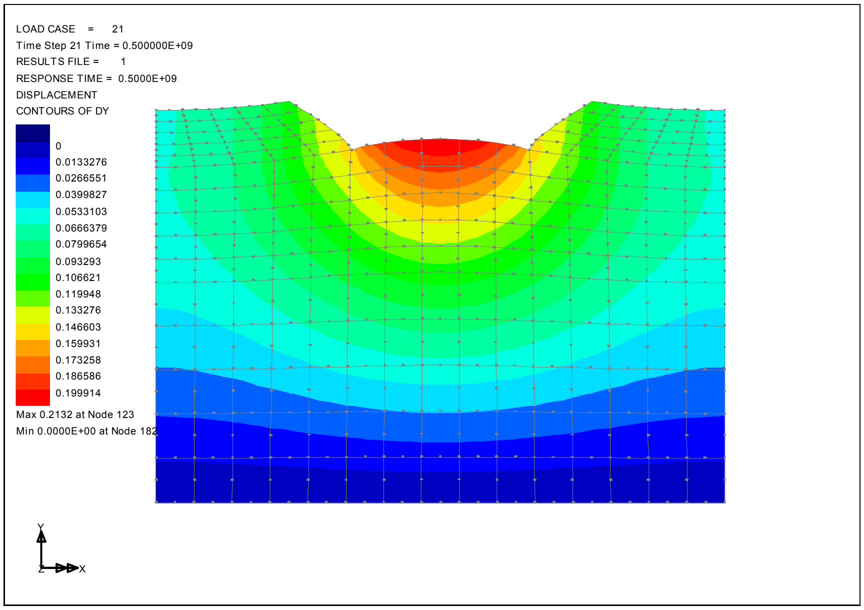

Figure 9: Vertical displacements for consolidation solution at T=∞

4. References

SIMONS, N.E. and MENZIES, B.K. (1977). “A short course in foundation engineering”. Butterworth & Co (Publishers) Ltd.