SVSOLID™

2D / 3D Stress Deformation Modeling Software

Verification Manual

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1 INTRODUCTION

The word “Verification”, when used in connection with computer software can be defined as “the ability of the computer code to provide a solution consistent with the physics defined by the governing partial differential equation, PDE”. There are also other factors such as initial conditions, boundary conditions, and control variables that also affect the accuracy of the code to perform as stated.

“Verification” is generally achieved by solving a series of so-called “benchmark” problems. “Benchmark” problems are problems for which there is a closed-form solution or for which the solution has become “reasonably certain” as a result of long-hand calculations that have been performed. Publication of the “benchmark” solutions in research journals or textbooks also lends credibility to the solution. There are also example problems that have been solved and published in User Manual documentation associated with other comparable software packages. While these are valuables checks to perform, it must be realized that it is possible that errors can be transferred from one’s software solution to another. Consequently, care must be taken in performing the “verification” process on a particular software package. It must also be remembered there is never such a thing as complete software verification for “all” possible problems. Rather, it is an ongoing process that establishes credibility with time.

SoilVision Systems takes the process of “verification” most seriously and has undertaken a wide range of steps to ensure that the SVSOLID software will perform as intended by the theory of saturated-unsaturated stress and deformation.

The following models represent comparisons made to textbook solutions, hand calculations, and other software packages. We at SoilVision Systems Ltd. are dedicated to providing our clients with reliable and tested software. While the following list of example models is comprehensive, it does not reflect the entirety of models, which may be posed to the SVSOLID software. It is our recommendation that water balance checking be performed on all model runs prior to presentation of results. It is also our recommendation that the modeling process move from simple to complex models with simpler models being verified through the use of hand calculations or simple spreadsheet calculations.

2 LINEAR ELASTIC MODEL

This Chapter will compare SVSOLID to other stress-deformation software to benchmark the linear elastic model.

2.1 STRIP FOOTING STRESSES COMPARISON

The *Strip Footing Stresses* model from Lambe & Whitman (1969) presents a closed form solution. Results are also compared to the Sigma/w software.

Project: Foundations
Model: Strip_Footing

2.1.1 Model Description

A 4m wide strip footing has been placed on a homogenous linear elastic material. The extents of the material model are 30m wide by 30m depth. In SVSOLID the total stress analysis option has been selected, which means the pore water pressure is 0 kPa throughout the model. A pressure of unity (1 kPa) has been applied so that the resulting contours are a ratio of the applied pressure.

2.1.1.1 Material Properties

$E = 100$ kPa
$\upsilon = 0.45$
$\gamma = 0$ kN/m^3

2.1.1.2 Geometry/Boundary Conditions

The extents of the material model are 30m wide by 30m depth.
Load Expression = -1 kPa, representing the strip footing.

2.1.2 Results

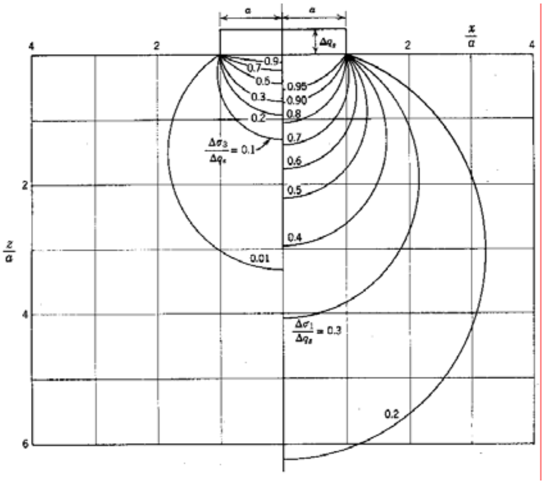

Figure 1- Strip Footing, Closed Form Solution - Pressure Bulb (Lambe & Whitman, 1969)

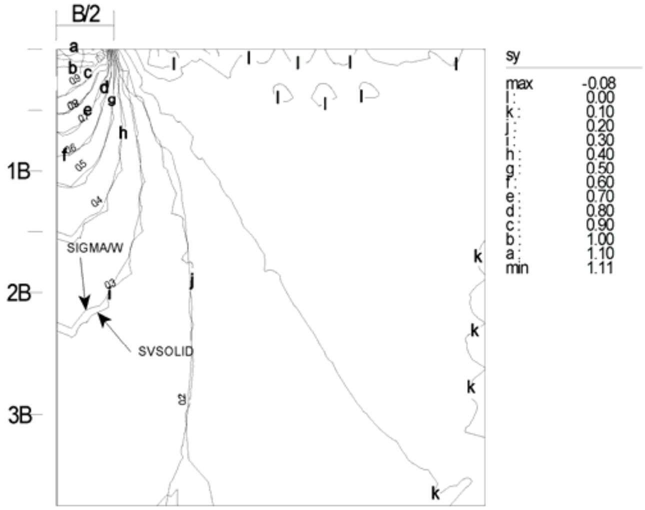

Figure 2- SVSOLID versus SIGMA/W

The pressure contours produced by SVSOLID are very close to those predicted by Lambe & Whitman and SIGMA/W. A comparison of the vertical stress contours to the depth below the centerline of the footing is outlined below in Table 1.

Table 1 - Comparison of Results

Contour	SIGMA/W	Lambe & Whitman	SVSOLID
0.8	0.53B	0.56B	0.53B
0.6	0.89B	0.89B	0.89B
0.5	1.13B	1.11B	1.10B
0.4	1.50B	1.48B	1.50B
0.3	2.27B	2.04B	2.25B

2.2 ROUND FOOTING STRESSES COMPARISON

The Circular Footing Stresses model from Lambe & Whitman (1979) presents a closed form solution for an Axisymmetric analysis. Results are also compared to the Sigma/w software.

Project: Foundations
Model: Round_Footing

2.2.1 Model Description

A 4m-radius strip footing has been placed on a homogenous linear elastic material. The extents of the material model are a 30m radius by 30m depth. In SVSOLID the total stress analysis option has been selected, which means the pore water pressure is 0 kPa throughout the model. A pressure of unity (1 kPa) has been applied so that the resulting contours are a ratio of the applied pressure.

2.2.1.1 Material Properties

E = 100 kPa
$\upsilon = 0.45$
$\gamma = 0$ kN/m^3

2.2.1.2 Geometry/Boundary Conditions

The extents of the material model are a 30m radius by a 30m depth.

Load Expression = -1 kPa, representing the circular footing.

2.2.2 Results

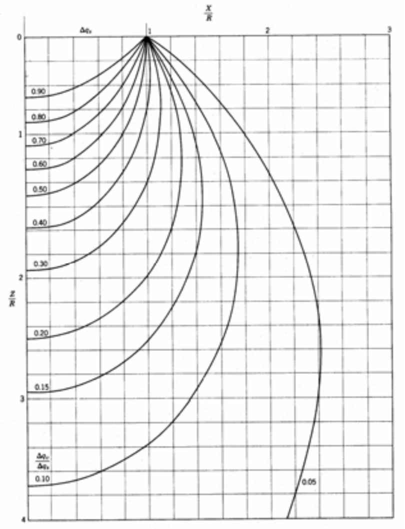

Figure 3- Round Footing, Closed Form Solution - Pressure Bulb (Lambe & Whitman, 1969)

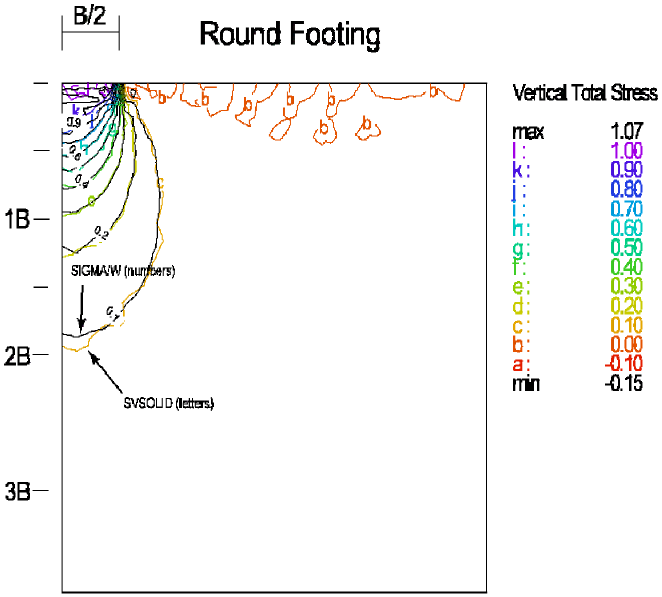

Figure 4- SVSOLID versus SIGMA/W

The pressure contours produced by SVSOLID are very close to those predicted by Lambe & Whitman and SIGMA/W. A comparison of the vertical stress contours to the depth below the centerline of the footing is outlined below in Table 2. Note that the stress contours for a round footing are similar in shape to those in the strip footing example above, except the size of the pressure bulb is much smaller.

Table 2 - Comparison of Results

Contour	SIGMA/W	Lambe & Whitman	SVSOLID
0.9	0.26B	0.25B	0.25B
0.7	0.44B	0.44 B	0.44B
0.5	0.64B	0.65B	0.63B
0.3	0.97B	0.97B	0.98B
0.2	1.24B	1.25B	1.28B

2.3 AXISYMMETRIC COMPARISON

The Example Model from Chapter 3, Tutorial Section, of the SIGMA/W User's Guide has been used as a comparison for the Axisymmetric capabilities of SVSOLID.

Project: Foundations
Model: Water_Tank_Stresses

2.3.1 Model Description

A 5m-radius water tank has been placed on a material column consisting of two layers. The extents of the material model are a 38m radius by 25m depth. In SVSOLID the total stress analysis option has been selected. A pressure of 40 kPa has been applied representing the weight of the water in the tank.

2.3.1.1 Material Properties

Top Layer:	Bottom Layer:
E = 3000 kPa	E = 4000 kPa
υ = 0.45	υ = 0.45
γ = 0 kN/m^3	γ = 0 kN/m^3

2.3.1.2 Geometry/Boundary Conditions

The material model is extended at a 38m radius so the model boundaries do not affect the model solution.

The top layer is 5m thick and the bottom layer is 20m thick.
Load Expression = -40 kPa, representing the weight of the circular tank.

2.3.2 Results

The pressure contours produced by SVSOLID are very close to those predicted by SIGMA/W. Figure 6 displays a Mohr Circle Diagram produced by both software products at approximately the same location (near 5.0, 20.0). The maximum displacement found by SIGMA/W is 0.0754m while that calculated by SVSOLID is 0.0764m.

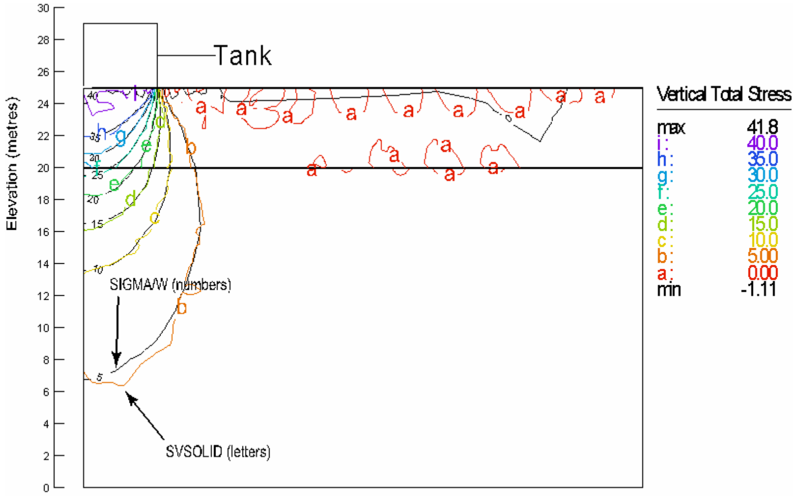

Figure 5 - SVSOLID versus SIGMA/W

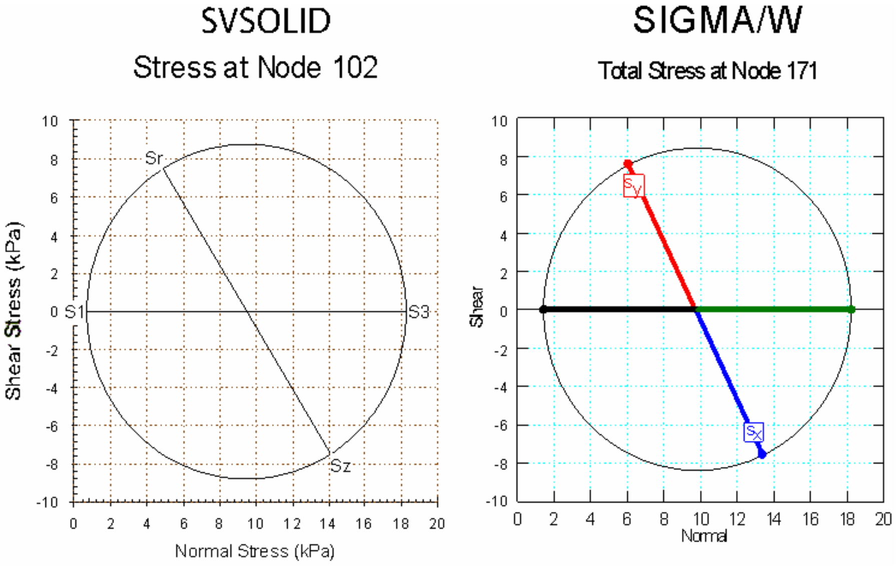

Figure 6 - SVSOLID versus SIGMA/W - Mohr Circle Diagram

3 NON-LINEAR ELASTIC MODEL

This Chapter will compare SVSOLID to the results from an ideal laboratory test to benchmark the non-linear elastic model.

3.1 OEDOMETER TEST

The non-linear elastic model was used to predict the vertical displacements for a block of material using material properties from an ideal oedometer test. The ability of the non-linear elastic model to follow the predicted void ratio versus stress relationship and calculate reliable vertical displacements will be shown.

Project:
Model:

3.1.1 Model Description

The model selected to perform the analysis consists of simple geometry and homogeneous material conditions. The geometry, material properties, and boundary conditions used for the analysis are described below.

3.1.1.1 Material Properties

The material properties listed in Table 3 were selected in order to produce a void ratio versus stress relationship with similar characteristics to a relationship produced from an actual laboratory test. Figure 7 shows the Gitirana void ratio versus stress relationship resulting from the selected material properties.

Table 3 - Material properties used for oedometer verification model

Slope of compression rebound curve (C_r)	0.1
Slope of virgin compression curve (C_c)	0.2
Pre-consolidation Pressure (P_p)	2000 kPa
Void ratio at 1 kPa (e_N)	0.6
Gitirana parameter (a_{gg})	0.01
Poisson's Ratio (μ)	0.45
Unit Weight (γ)	1 kN/m^3

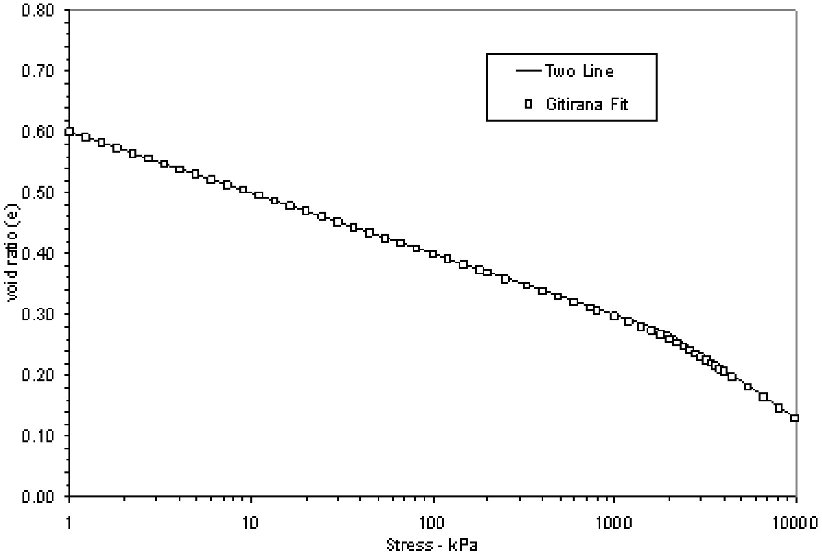

Figure 7- Void ratio versus stress relationship resulting from the material properties selected for the oedometer verification model.

3.1.1.2 Geometry/Boundary Conditions

The geometry, loading, and boundary conditions used for the analysis are illustrated in Figure 8. A simple 1m x 1m block of homogeneous material was analyzed. Roller boundary conditions were applied to the sides of the sample while the bottom of the sample was fixed. An initial load of 100 kPa was applied to the top of the sample. Additional load was applied to the sample in 200 kPa increments up to a total load of 3000 kPa. The vertical displacements resulting from each load increment were predicted.

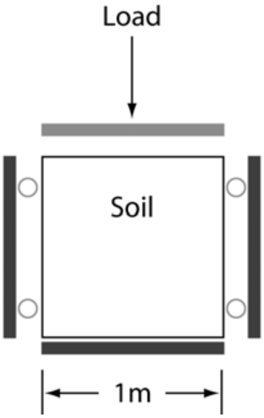

Figure 8 - Geometry, loading, and boundary conditions used for the oedometer verification model.

3.1.2 Results

The void ratios predicted by SVSOLID for each stress increment match the corresponding void ratios from the Gitirana fit. The Gitirana fit predicts slightly lower void ratios than the Two Line fit near the pre-consolidation pressure. The non-linear elastic formulation is based on the Gitirana fit, therefore, it should be expected that SVSOLID will predict slightly larger vertical displacements near the pre-consolidation pressure when compared to hand calculations based on the Two Line fit.

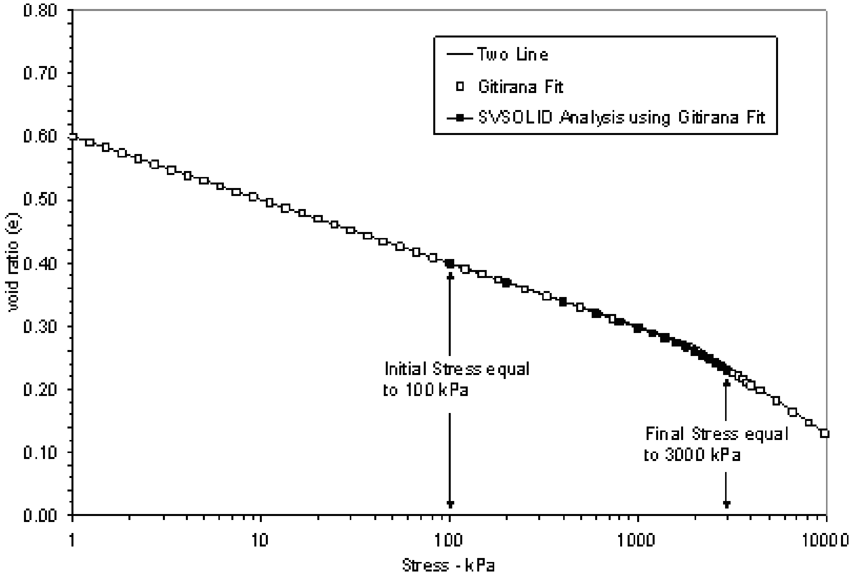

Figure 9 - Comparison of the void ratio predicted by SVSOLID for each stress increment with the Gitirana Fit and Two Line fit.

The vertical displacements predicted by SVSOLID for each stress increment are in good agreement with the vertical displacements calculated by hand using the Two Line fit. The vertical displacement resulting from a load of 3000 kPa was predicted to be 120.9 mm by SVSOLID. The vertical displacement calculated by hand using the Two Line fit was 118.1 mm as shown below.

Expected settlement prior to reaching the pre-consolidation pressure:

$$S = C_r \frac{H}{1+e_0} \log \frac{\sigma}{\sigma_{v0}} = (0.1)\frac{1}{1+0.4} \log \frac{2000}{100} = 0.0929m$$

Expected settlement after reaching the pre-consolidation pressure:

$$S = C_c \frac{H}{1+e_0} \log \frac{\sigma}{\sigma_{v0}} = (0.2)\frac{1}{1+0.4} \log \frac{3000}{2000} = 0.0251m$$

Total settlement expected = 0.0929+0.025= 0.118 m

The vertical displacements predicted by SVSOLID are slightly larger near the pre-consolidation pressure corresponding with the differences observed in the void ratio versus stress relationships shown in Figure 10.

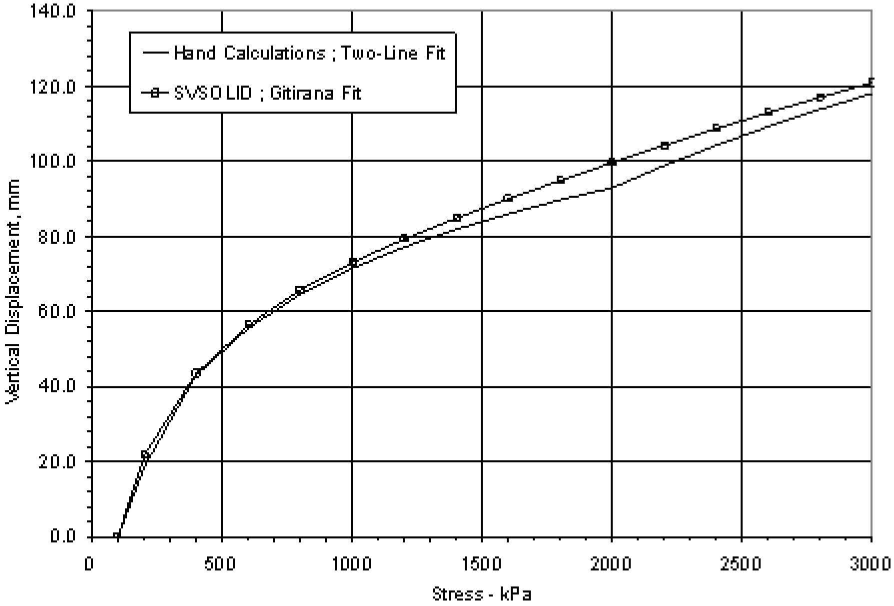

Figure 10 - Comparison of the vertical displacements predicted by SVSOLID for each stress increment with the hand calculations based on the Two Line fit.

4 SIGN CONVENTION

This section will cover the sign conventions used in SVSOLID.

4.1 BOUNDARY CONDITION EXPRESSIONS

Load and Displacement Boundary Conditions follow the same coordinate system as defined for material displacement. In 2D a positive *x* Load Expression will act to the right and a positive *y* Load Expression will act up. The same is true for an *x* Displacement Expression or *y* Displacement Expression.

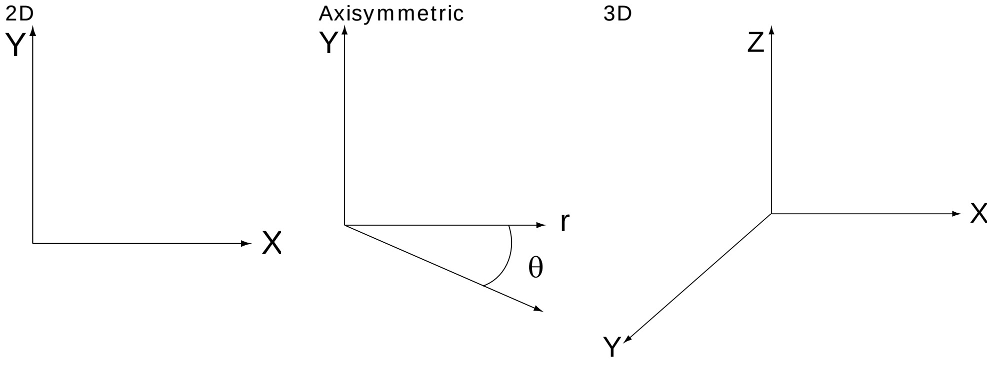

Figure 11

Project: StressBasics
2D Model: LoadBC1 to LoadBC4
Axisymmetric Model: LoadBC_A1 to LoadBC_A3
3D Model: Load3D1 to Load3D6

4.1.1 Model Description

In 2D and Axisymmetric a unit square is defined. In each case a Load Expression = -100 kPa is applied to one side. The opposite side is fixed in both directions and the remaining 2 sides are fixed in the direction perpendicular to the load. In 3D a unit cube is used and the same procedure applied. A simple Linear Elastic material is used and no body load is applied.

Note that in the following diagrams the arrow indicating a load boundary condition does not indicate the direction of the load, only the presence of the boundary condition.

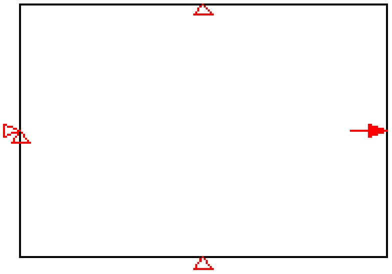

Figure 12- Load Boundary Conditions 2

4.1.2 Results

Each model indicated above demonstrates the boundary condition sign convention on a different face of the unit square or cube. The results of Model Name: LoadBC2 are shown here.

Note that in the SVSOLID sign convention positive stress indicates compression.

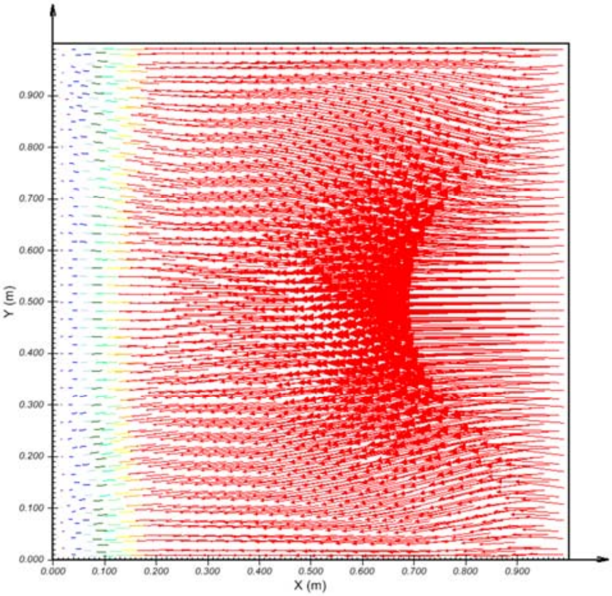

Figure 13- LoadBC2 Displacement Vectors

4.2 BODY LOAD DIRECTION

The body load sign convention follows that of displacements and boundary conditions. A negative *y* body load acts down simulating gravity.

Project: StressBasics
Model: BodyLoadSign

4.2.1 Model Description

A body load of –21 kN/m^3 has been assigned to a Linear Elastic material unit square. The base has been fixed in both directions and the vertical sides are fixed in the *x* direction.

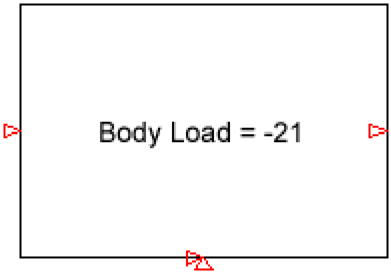

Figure 14- Body Load

4.2.2 Results

The following results show the displacements as down and compressive stresses due to the body load.

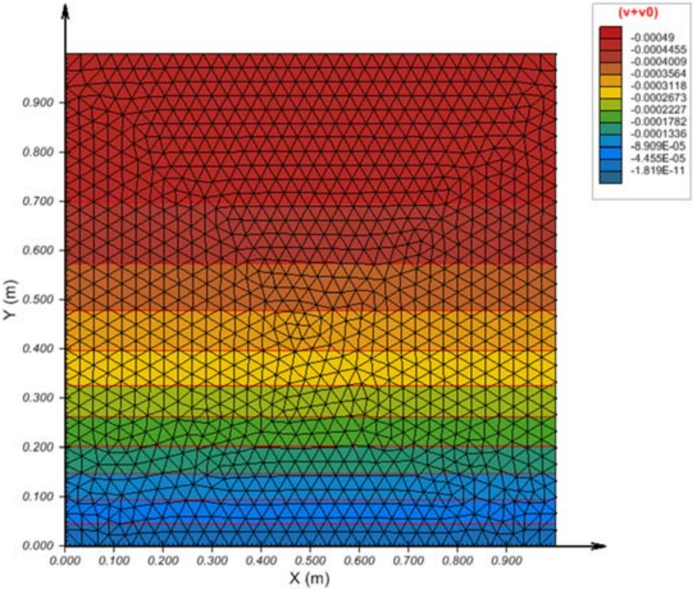

Figure 15- Body Load Displacement Vectors

4.3 SHEAR STRESS ORIENTATION

This model demonstrates the shear stress orientation in SVSOLID as illustrated in the following diagram.

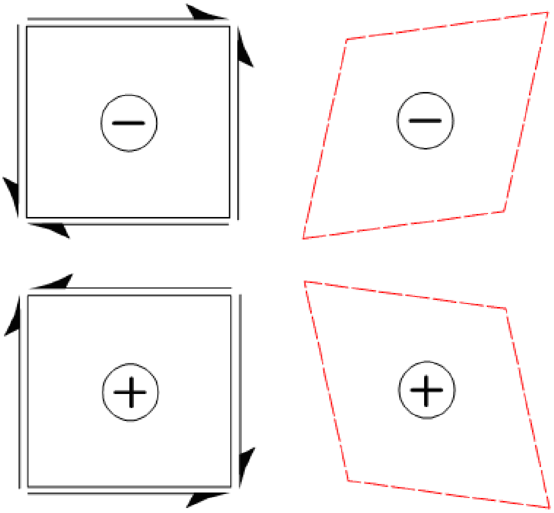

Figure 16- Shear Stress Diagram

Project: StressBasics
Model: ShearStress_Negative, ShearStress_Positive

4.3.1 Model Description

A unit square is defined and Displacement Expression boundary conditions are applied each with a value of 0.1. The arrows on the above diagram indicate the boundary condition directions. A simple Linear Elastic material is used for the unit square.

4.3.2 Results

These results display the shear stress orientation for positive shear.

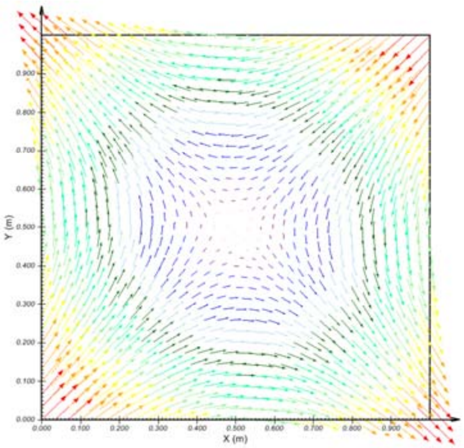

Figure 17 - Shear Displacement Vectors

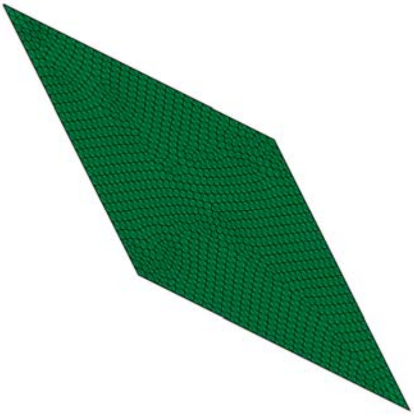

Figure 18 - Shear Stress Mesh

4.4 REGION SHAPE DIRECTION

Polygon region shapes in SVSOLID can be drawn in either a clockwise or counter-clockwise fashion. The following explanation reveals that the SVSOLID Solver calculates the effects of a load boundary condition independent of the direction that the region shape was entered.

Project: StressBasics
Model: Clockwise Model Name is ShapeDirectionCW.
Counter-clockwise Model Name is *ShapeDirectionCCW*.

4.4.1 Model Description

A unit square has been drawn and assigned a simple till material. The material properties are a Young's Modulus, *E* = 10000 kPa and a Poisson's Ratio, ν = 0.4. A load of -100 kPa is applied to the top boundary between 0.25m and 0.75m. No body load is present.

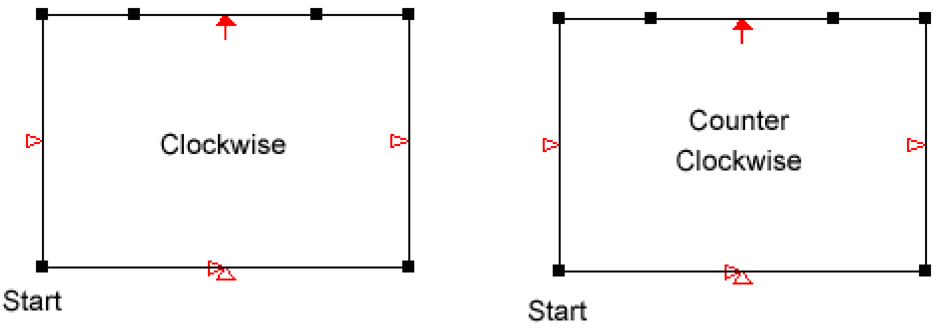

Figure 19

4.4.2 Results

The following results give the same vertical stress profiles for both models indicating that boundary condition loading is independent of the direction that the polygon region shape was drawn.

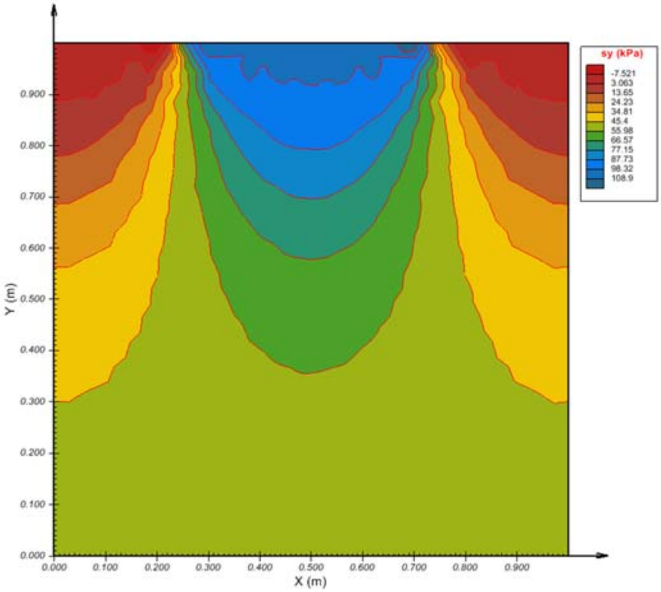

Figure 20 - Clockwise Stress Contours

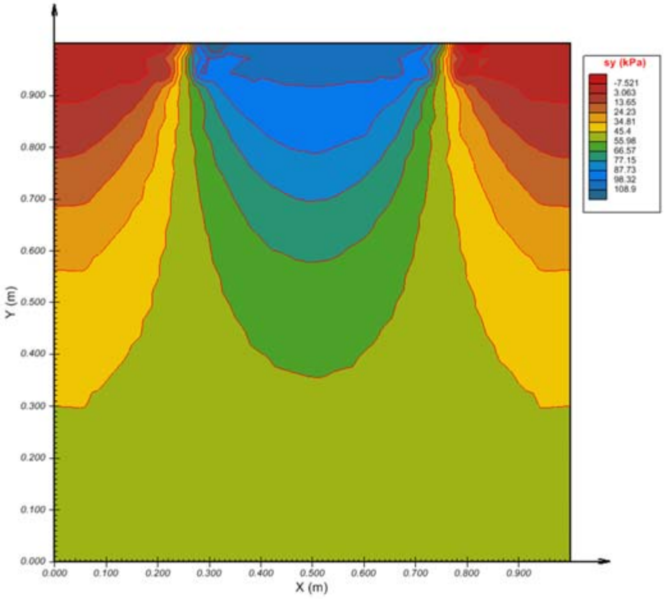

Figure 21 - Counter-Clockwise Stress Contours

5 BOUNDARY CONDITIONS

This section will outline spring boundary conditions that can be applied in SVSOLID.

5.1 SPRING EXPRESSIONS

Spring boundary conditions can be applied in SVSOLID. The force exerted on a boundary is proportional to the displacement at that boundary.

$F = ku$ where k is the spring constant

In SVSOLID entering a spring equation as a load or displacement boundary condition expression creates a spring boundary condition.

Project: StressBasics
Model: Spring1, Spring2

5.1.1 Model Description

A unit square consisting of a simple Linear Elastic is used. No body load is applied.

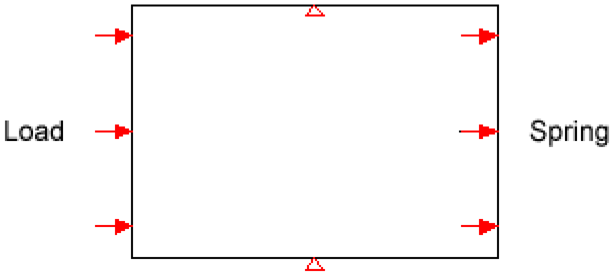

Figure 22 - Spring Boundary Condition

A load of 100 kPa is applied on the left boundary. A spring constant of 800 N/m has been arbitrarily chosen.

In model Spring1 a Displacement Expression = $sx/800$ is specified for the right boundary.
In model Spring2 a Load Expression = $-800*u$ is specified for the right boundary.

5.1.2 Results

Both models produce the following results. The x displacement on the right boundary is 0.125m.

$u = sx/k$ = 100 kPa / 800 N/m = 0.125m

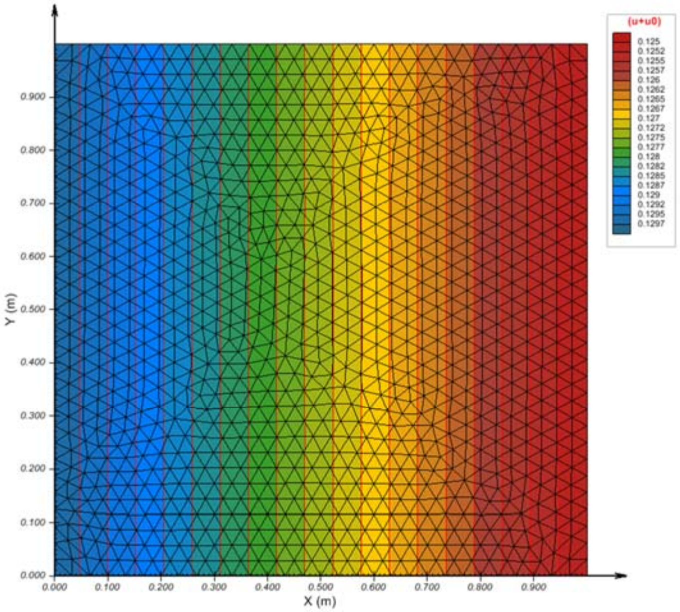

Figure 23 - Spring Expression - Stress Contours

6 IN-SITU STRESSES

This section involves in-situ stresses are examined where a load is applied.

6.1 IN-SITU INITIAL STRESS VERSUS NO INITIAL STRESS COMPARISON

This comparison examines the difference in results between using in-situ stresses as initial conditions for a second run where a load is applied and applying the body load along with the load as one run.

Project: StressBasics
Model: InitialStressFile, InitialStressNoFile

6.1.1 Model Description

The models consist of a unit square that contains a simple Linear Elastic material. The square is fixed in both directions at the base and fixed in the *x* direction on the sides. The material used has a *y* Body Load = -21 kN/m^3.

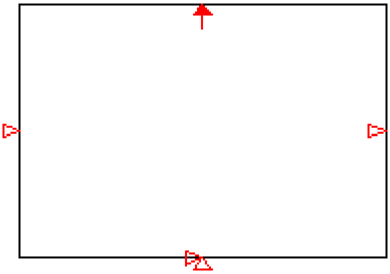

Figure 24 - In-Situ Stress

6.1.1.1 In-Situ Initial Stress

In the model InitialStressFile the initial stresses from the model BodyLoadSign are used. In BodyLoadSign only the body load is applied to the above unit cube. The file path to BodyLoadSign is specified on the Settings form in SVSOLID and only the stress values are chosen for import. A load of 100 kPa is applied to the top of the square between 0.25m and 0.75m. The body load of –21 kN/m^3 remains for the material.

6.1.1.2 No In-Situ Initial Stress

In the model InitialStressNoFile the body load of –21 kN/m^3 is present for the material and the load of 100 kPa is applied to the top of the square between 0.25m and 0.75m.

6.1.2 Results

The final stress state is the same in both scenarios while using in-situ initial stress does not consider deformations caused by the body load. For the model InitialStressFile the resulting maximum deformation is 0.0039m while in InitialStressNoFile the maximum deformation is 0.0045m.

When using in-situ initial stresses it was assumed that the actual model geometry was already deformed due to the gravity loading. Therefore, the stress values due to the body load and not any deformation values were used as initial conditions for the second stage of the model. As a result only the deformations caused by the applied 100 kPa are experienced.

In-Situ Initial Stress Plots

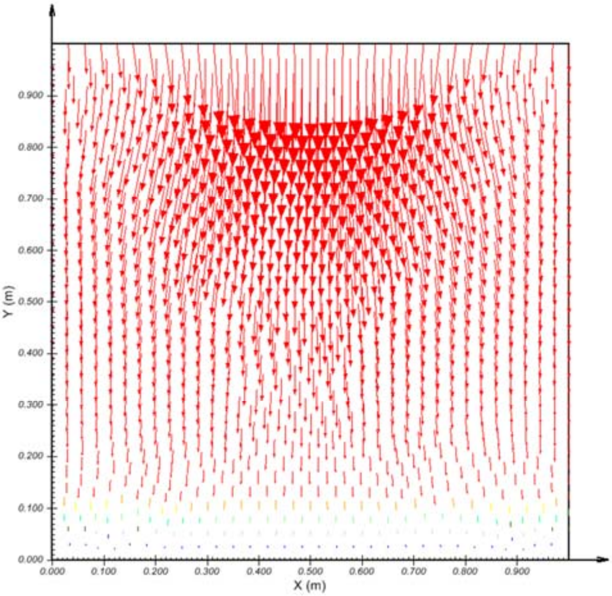

Figure 25 - In-Situ Initial Stress - Displacements

No In-Situ Initial Stress Plots

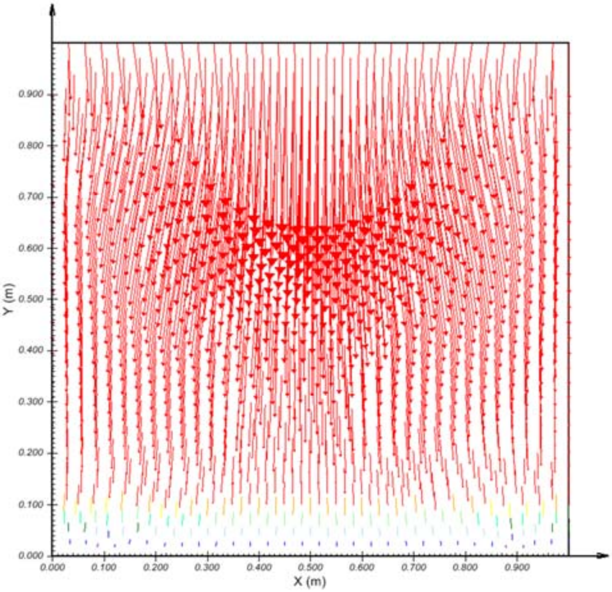

Figure 26 - No In-Situ Initial Stress - Displacements

7 2D EDGE DROP

This section involves the edge drop of a flexible impervious cover due to evaporation.

7.1 OBJECTIVE

The objective of this study is to verify the results of the SVFLUX seepage analyses and SVSOLID stress/deformation analyses against the model presented by Fredlund, D. G., and Vu, H. Q. in the paper *Numerical modeling of swelling and shrinking soils around slabs-on-ground* submitted for the PTI California conference in 2002. The model involves the edge-drop of a flexible impervious cover due to evaporation.

7.2 SEEPAGE VERIFICATION WITH SVFLUX

In this section, the SVFLUX seepage analysis results will be examined.

7.2.1 Method

The flow regime must first be set up in SVFLUX.

7.2.1.1 Model Geometry

A single section of material 12m long x 1m wide x 3m deep is present. The flexible cover extends over half the ground surface and divides the model into 2 regions.

7.2.1.2 Boundary Conditions

A constant suction of 400 kPa is maintained at the bottom boundary. No flow is permitted at the edge boundaries and beneath the cover. An evaporation rate is applied to the uncovered top boundary. The following diagram represents a two-dimensional slice along the *y*-axis.

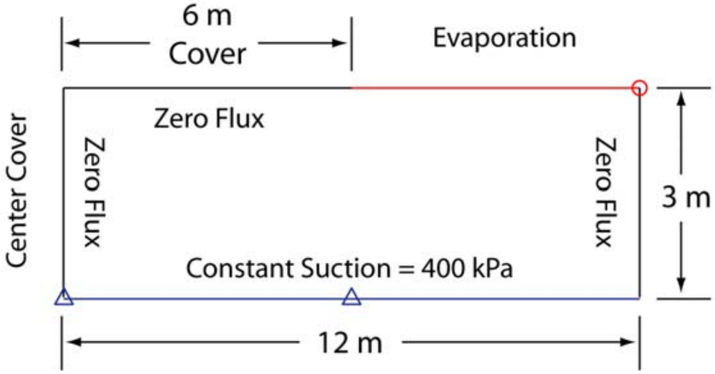

Figure 27 - Applied Seepage Boundary Conditions

7.2.1.3 Material Properties

The following material properties were used:

Table 4 - Assumed material properties for seepage analysis.

Material Properties	Values
Coefficient of permeability at saturation, k_s	1x10-8 m/s
Volumetric water content at saturation, q_s	0.45
Parameters for SWCC (Fredlund & Xing, 1994) and permeability function (Leong and Rahardjo, 1997)	a = 300 kPa
	n = 1.5
	m = 1
	p = 1

7.2.1.4 Initial Conditions

An initial run was performed to establish the initial conditions for the edge-drop model. A constant suction of 400 kPa was set at the bottom boundary while a constant suction of 20 kPa was set at the ground surface. This established a linear suction profile.

Project: SlabOnGround
Model: ShrinkInitial

7.2.2 Results

The results of the SVFLUX analyses match those presented by Fredlund & Vu.

Transient Analysis

Project: SlabOnGround
Model: ShrinkTransient

An analysis was performed with an evaporation rate of 10 mm/day. The results exactly match those of the 2D scenario. Figure 28 indicates high suction gradient approximately 1 m from the cover edge while the suction is uniform elsewhere. This chart matches the results of Fredlund & Hung. Figure 29 displays the suction versus depth and shows that most of the suction change occurred near the ground surface. A pore-water pressure profile at day 3 can be seen in Figure 30.

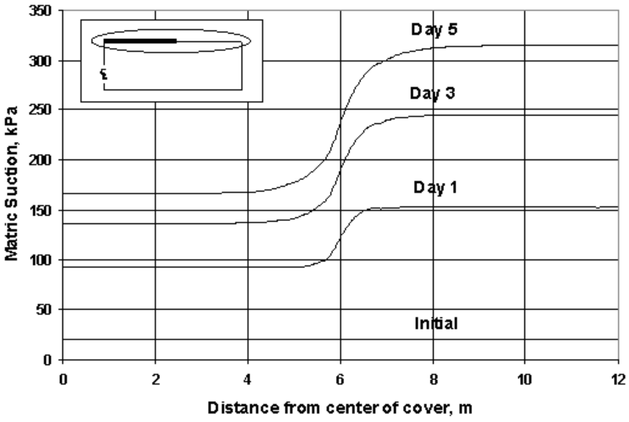

Figure 28 - Matric suctions at the ground surface for various elapsed evaporation times.

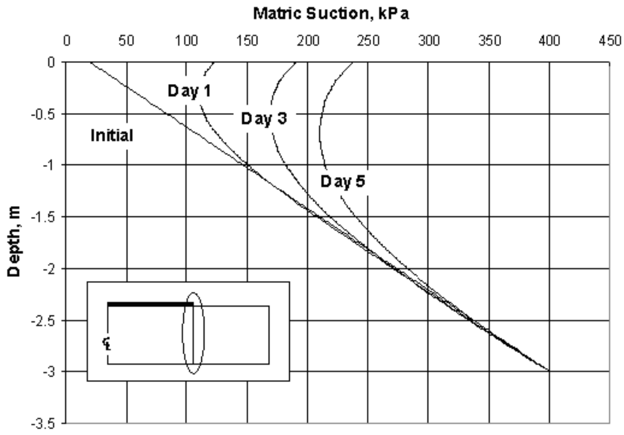

Figure 29 - Matric suction profiles at the edge of the cover for various elapsed evaporation times.

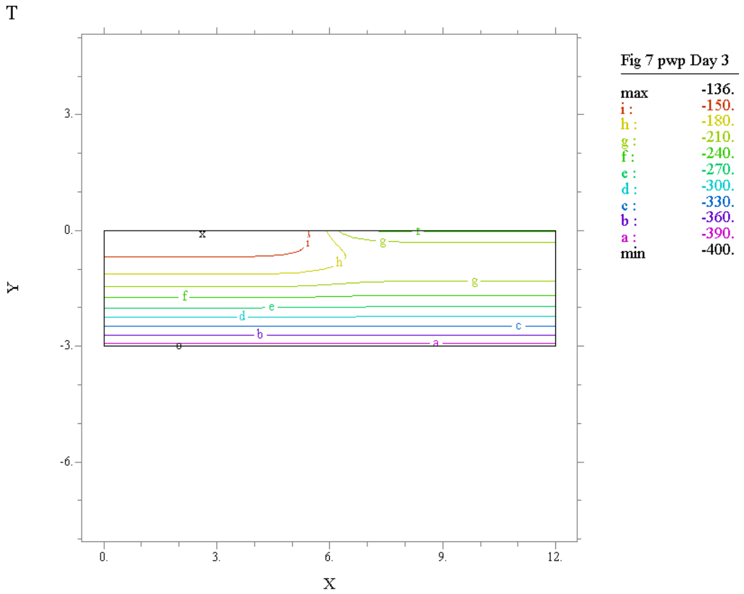

Figure 30 - Contours of pore-water pressure after three days of evaporation.

7.3 STRESS VERIFICATION WITH SVSOLID

In this section, the SVSOLID stress analysis to determining the amount of vertical deformation, which is experienced at the edge of the concrete slab due to a drying event and subsequent soil shrinkage.

7.3.1 Method

The same geometry is used for this model as for the previous SVFLUX model. The previous seepage model established the initial and final pore-water pressure distributions. This model will calculate the amount of deformation (shrinkage), which will result from this change in pore-water pressures.

Project:	SlabOnGround
Model:	Day5Shrink

7.3.1.1 Model Geometry

A single material region 12m wide x 3m deep is present. The flexible cover extends 6m from the left boundary:

7.3.1.2 Boundary Conditions

The left and right boundaries are fixed in the *x*-direction and free to move in the *y*-direction. The bottom boundary is fixed in both the *x* and *y* directions while the top boundary (ground surface) is free to move.

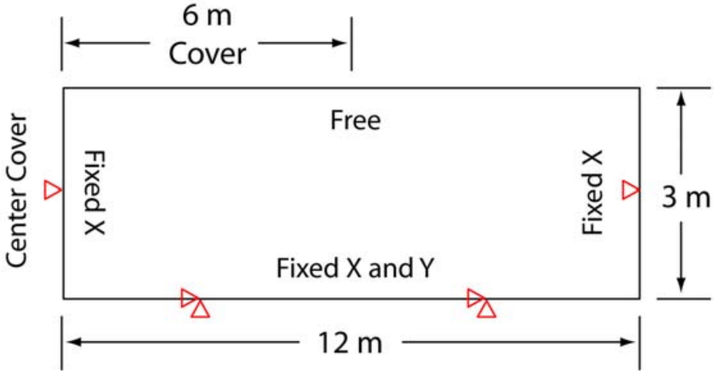

Figure 31 - Applied stress boundary conditions.

7.3.1.3 Material Properties

The following material properties were used:

Table 5 - Assumed material properties for stress analysis.

Material Properties	**Values**
Total Unit Weight, γ_t	17.2 kN/m^2
Initial Void Ratio, *eo*	1
Swelling Index, C_s	0.15
Swelling Index, C_m	0.13
Poisson's Ratio, μ_s	0.4
Coefficient of earth pressure at rest, K_o	0.33

7.3.1.4 Analysis

The model conditions are defined by providing an initial stress state, an initial pore-water pressure, and a final pore-water pressure.

The initial vertical stress-state in the material is determined from the total unit weight multiplied by the elevation (the depth below the datum of 0). The horizontal stress is determined from the vertical stress by applying the coefficient of earth pressure at rest, K_o.

The initial pore-water pressure conditions are the same as those defined for the SVFLUX seepage analysis. A constant suction of 400 kPa was set at the bottom boundary while a constant suction of 20 kPa was set at the ground surface. This established a linear suction profile. The pore-water pressure transfer file output by the initial SVFLUX run is set as the initial pore-water pressure for the stress analysis.

The final pore-water pressure conditions are set as the final pore-water pressure transfer file output by the SVFLUX seepage analysis. For example, when modeling the deformations after 1 day the pore-water pressure file is that output after 1 day of the SVFLUX transient analysis.

7.3.2 Results

SVSOLID analyses were performed to model the movement of the material after 5 days of evaporation at a rate of 10 mm/day. Figure 32 shows the vertical displacement in the material after different evaporation periods. After 5 days of evaporation the differential settlements is about 10 mm. This differential settlement matches the results of Fredlund & Hung, but overall the displacements calculated by SVSOLID are 3mm less. Figure 32 displays the vertical displacement versus depth at the edge of the cover. It shows that most of the settlement occurred within 1m of the ground surface where the change in matric suction is greatest and the material has a lower elastic modulus. A vertical displacement profile at day 3 can be seen in Figure 33.

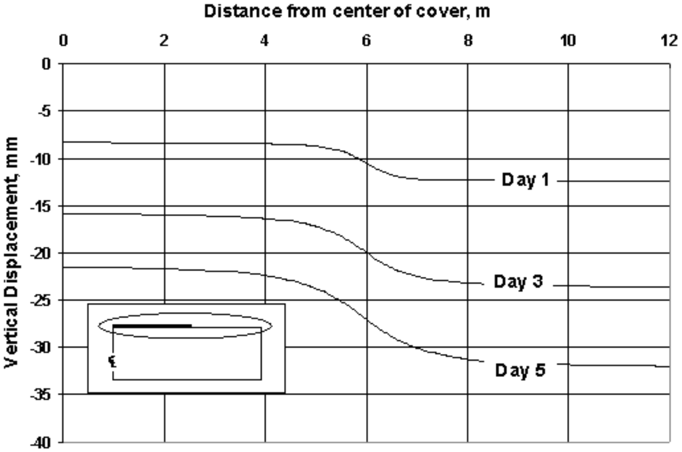

Figure 32- Vertical displacements at ground surface for various elapsed times of evaporation.

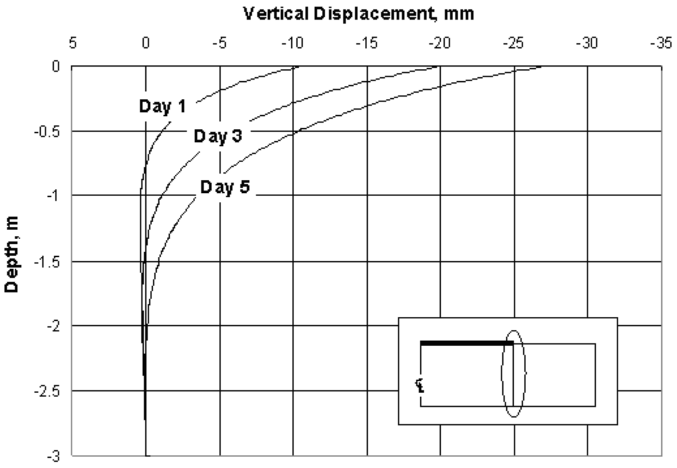

Figure 33 - Vertical displacements versus depth at the edge of the cover for various elapsed evaporation times.

8 3D: THIN SLAB

The model involves the edge-drop of a flexible impervious cover in three-dimensions due to evaporation.

8.1 OBJECTIVE

The objective of this study is to verify the results of the SVFLUX seepage analyses and SVSOLID stress/deformation 3D analyses. They will be verified against the 2D model presented by Fredlund, D. G., and Hung Q. V. in the paper *Numerical modeling of swelling and shrinking soils around slabs-on-ground*, submitted for the PTI California Conference in 2002. The model involves the edge-drop of a flexible impervious cover due to evaporation. The 2D model has been extended 1m in the third direction.

8.2 SEEPAGE VERIFICATION WITH SVFLUX

In this section, the SVFLUX seepage analysis results will be examined.

8.2.1 Method

A thin model is set up in SVFLUX consisting of upper and lower 3D surfaces. The intent is to first ascertain the initial and final pore-water pressure conditions.

8.2.1.1 Geometry

A single section of material 12m long x 1m wide x 3m deep is present. The flexible cover extends over half the ground surface and divides the model into 2 regions.

8.2.1.2 Boundary Conditions

A constant suction of 400 kPa is maintained at the bottom boundary. No flow is permitted at the edge boundaries and beneath the cover. An evaporation rate is applied to the uncovered top boundary. The following diagram represents a two-dimensional slice along the *y*-axis.

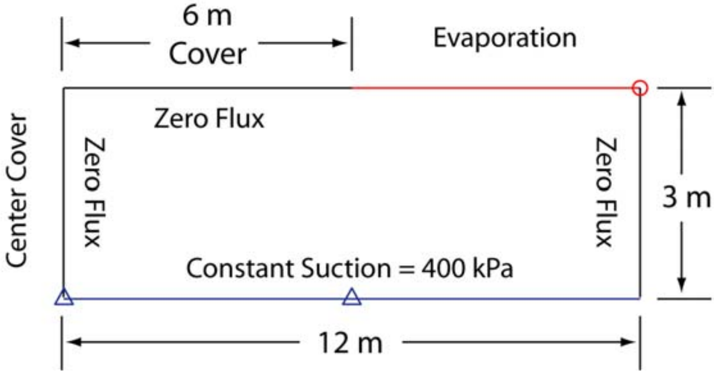

Figure 34 - Applied Seepage Boundary Conditions

8.2.1.3 Material Properties

The following material properties were used:

Table 6 - Assumed material properties for seepage analysis.

Material Properties	Values
Coefficient of permeability at saturation, k_s	1x10-8 m/s
Volumetric water content at saturation, q_s	0.45
Parameters for SWCC (Fredlund & Xing, 1994) and permeability function (Leong and Rahardjo, 1997)	a = 300 kPa
	n = 1.5
	m = 1
	p = 1

8.2.1.4 Initial Conditions

An initial run was performed to establish the initial conditions for the edge-drop model. A constant suction of 400 kPa was set at the bottom boundary while a constant suction of 20 kPa was set at the ground surface. This established a linear suction profile.

Project: SlabOnGround
Model: ShrinkSlice3D_Initial

8.2.2 Results

A transient analysis was performed with an evaporation rate of 10 mm/day. The results exactly match those of the 2D scenario.

Project: SlabOnGround
Model: ShrinkSlice3D_Transient

Figure 35 indicates high suction gradient approximately 1 m from the cover edge while the suction is uniform elsewhere. This chart matches the results of Fredlund & Hung. Figure 36 displays the suction versus depth and shows that most of the suction change occurred near the ground surface. A pore-water pressure profile at day 3 can be seen in Figure 37.

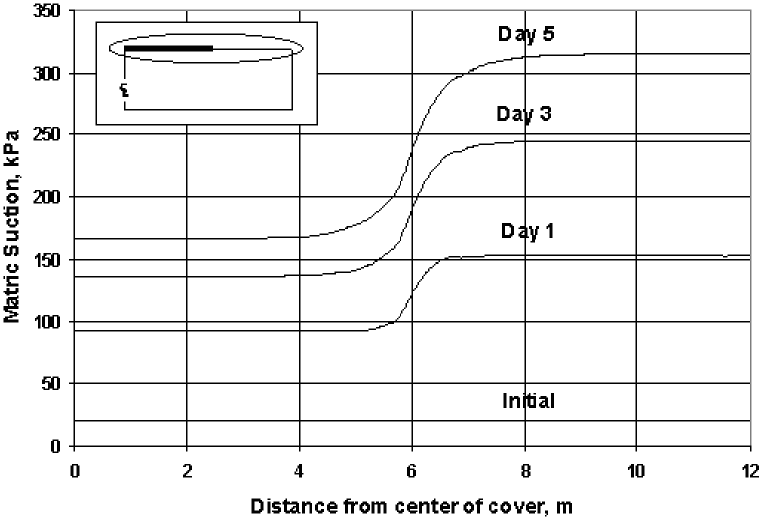

Figure 35 - Matric suctions at the ground surface for various elapsed evaporation times.

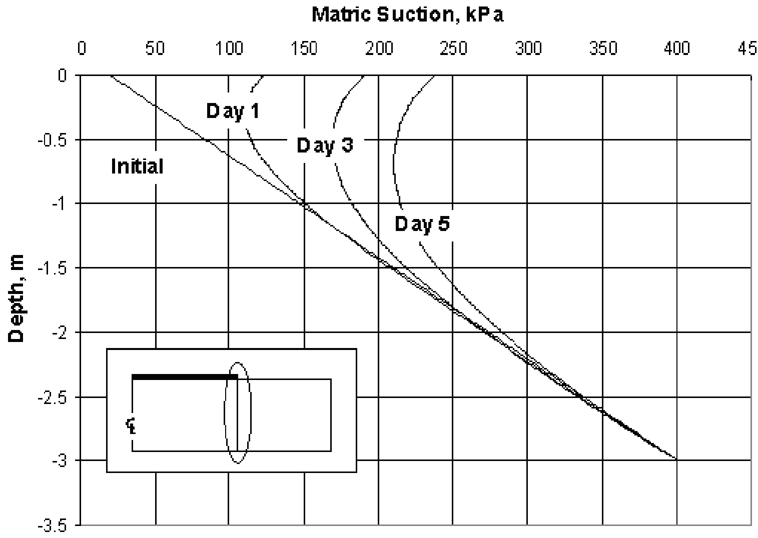

Figure 36 - Matric suction profiles at the edge of the cover for various elapsed evaporation times.

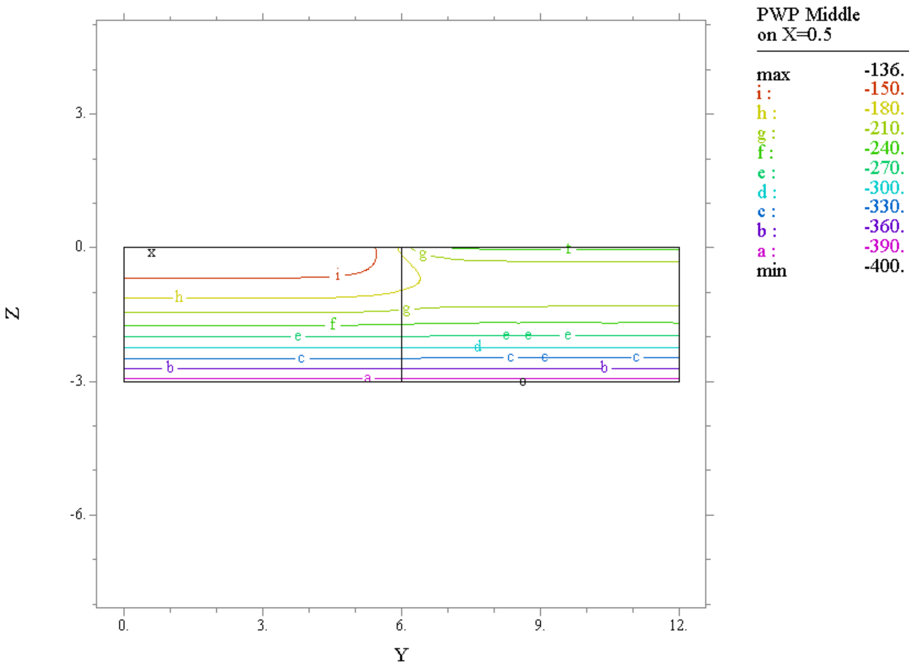

Figure 37 - Contours of pore-water pressure after three days of evaporation.

8.3 STRESS VERIFICATION WITH SVSOLID

In this section, the SVSOLID stress analysis results will be performed in order to calculate the vertical displacement created as a result of the increase in soil suction.

8.3.1 Method

The same geometry is usd as for the SVFLUX calculation of pore-water pressures. Stress-based boundary conditions will be entered which one consistent with the analysis.

8.3.1.1 Model Geometry

A single section of material 12m long x 1m wide x 3m deep is present. The flexible cover extends over half the ground surface and divides the model into 2 regions.

8.3.1.2 Boundary Conditions

The east and west boundaries are fixed in the *x*-direction and free to move in the *y*-direction and *z*-direction. The north and south boundaries are fixed in the *y*-direction and free to move in the *x*-direction and *z*-direction. The bottom boundary is fixed in all directions while the top boundary (ground surface) is free to move.

8.3.1.3 Material Properties

The following material properties were used:

Table 7 - Assumed material properties for stress analysis.

Material Properties	**Values**
Total Unit Weight, γ_t	17.2 kN/m^2
Initial Void Ratio, e_o	1
Swelling Index, C_s	0.15
Swelling Index, C_m	0.13
Poisson's Ratio, μ_s	0.4
Coefficient of earth pressure at rest, K_o	0.33

8.3.1.4 Analysis

The model conditions are defined by providing an initial stress state, an initial pore-water pressure, and a final pore-water pressure.

Project: SlabOnGround
Model: ShrinkSlice3D_Day5

The initial vertical stress-state in the material is determined from the total unit weight multiplied by the elevation (the depth below the datum of 0). The horizontal stress is determined from the vertical stress by applying the coefficient of earth pressure at rest, K_o.

The initial pore-water pressure conditions are the same as those defined for the SVFLUX seepage analysis. A constant suction of 400 kPa was set at the bottom boundary while a constant suction of 20 kPa was set at the ground surface. This established a linear suction profile. The pore-water pressure transfer file output by the initial SVFLUX run is set as the initial pore-water pressure for the stress analysis.

The final pore-water pressure conditions are set as the final pore-water pressure transfer file output by the SVFLUX seepage analysis. For example, when modeling the deformations after 1 day the pore-water pressure file is that output after 1 day of the SVFLUX transient analysis.

8.3.2 Results

SVSOLID analyses were performed to model the movement of the material after 5 days of evaporation at a rate of 10 mm/day. The 3D analysis results in displacements that are less than the 2D scenario by approximately 6%.

Figure 38 shows the vertical displacement in the material after different evaporation periods. After 5 days of evaporation the differential settlements is about 10 mm. This differential settlement matches the results of Fredlund & Hung, but overall the displacements calculated by SVSOLID are 3 – 5 mm less.

Figure 39 displays the vertical displacement versus depth at the edge of the cover. It shows that most of the settlement occurred within 1m of the ground surface where the change in matric suction is greatest and the material has a lower elastic modulus. A vertical displacement profile at day 3 can be seen in Figure 40.

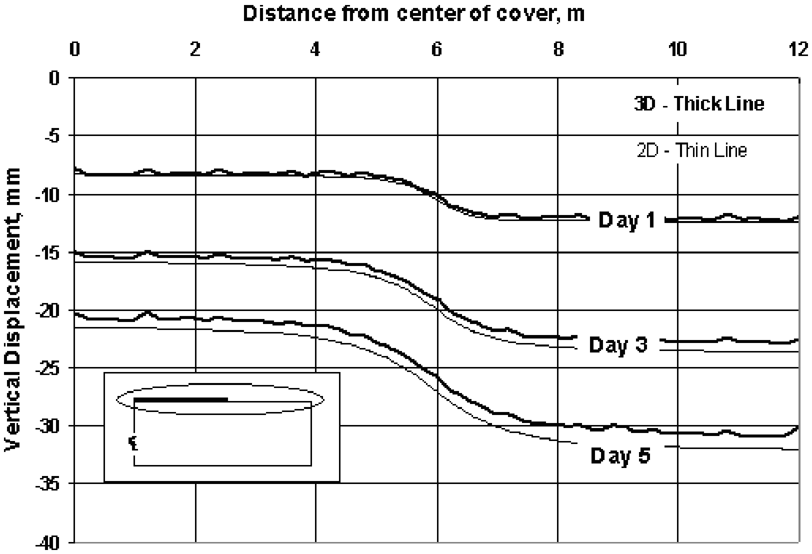

Figure 38 - 3D versus 2D -Vertical displacements at ground surface for various elapsed times of evaporation.

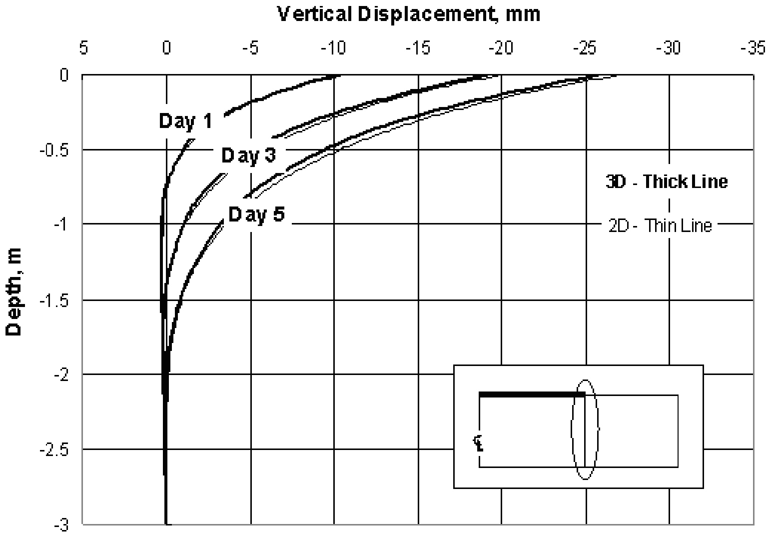

Figure 39 - 3D versus 2D -Vertical displacements versus depth at the edge of the cover for various elapsed evaporation times.

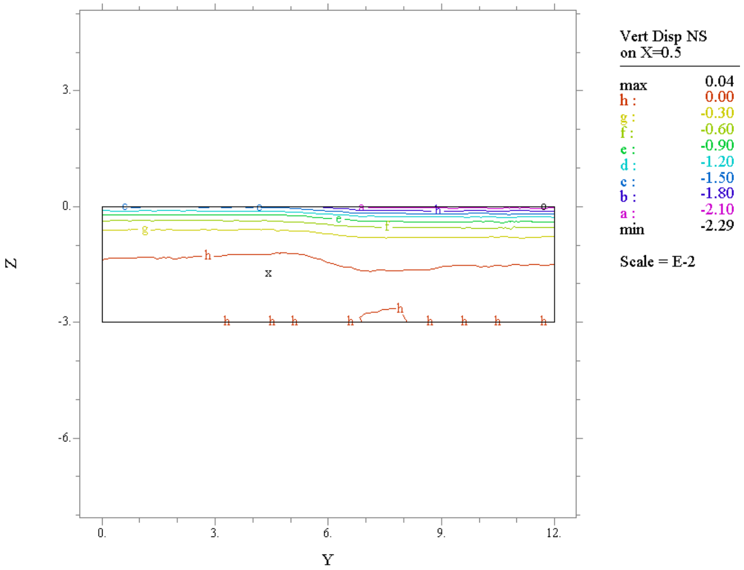

Figure 40 - Contours of vertical displacement after three days of evaporation.

8.3.3 Summary of Stress Verification

The summary of the modeling comparison of 3D SVFLUX to the 2D results of SVFLUX by SoilVision Systems Ltd. indicates the following:

- The 3D analysis results in displacements that are less than the 2D scenario by approximately 6%.

- The 3D settlement results are close for the edge-drop scenario caused by evaporation (within 5mm of deformation at the ground surface) to the results presented by Fredlund and Hung in *Numerical modeling of swelling and shrinking soils around slabs-on-ground*. The differential settlement results match.

Some positive displacement is encountered below the cover edge at lower depths. This phenomenon decreases with a longer period of evaporation. Tensile stresses developing in the material due to the fixed boundaries nearby and the large void ratio changes near the ground surface may cause it.

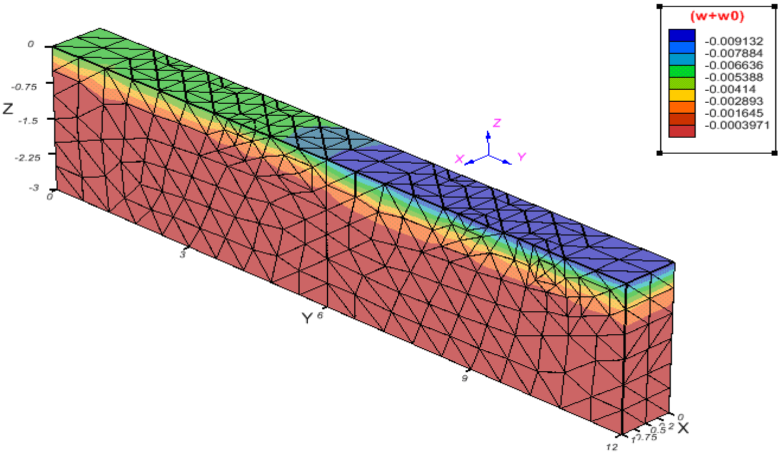

Figure 41 - Summary of vertical displacements as presented in the ACUMESH software.

9 REFERENCES

Fredlund, D. G., and Vu, H. Q. (2002). "Numerical modeling of swelling and shrinking soils around slabs-on-ground." Post-Tensioning Institute Conf., Huntington Beach, Calif., 125–132.

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