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Introduction to the examples

The examples in this Manual cover seven distinct landfill scenarios (summarised below); with minor adjustments, fourteen simulations are presented. The simulations have been created to show the potential of the HBM model and to illustrate model building, analysis, and interpretation using the graphical user interface.

Example	Geometry	Materials	Filling	Initial cond	Duration	Infiltration
1	2d section	Waste	No	Hydrostatic	500 d	No
2	2d section	Waste	No	Hydrostatic	500 d	500 mm
3	2d section	Waste	No	Hydrostatic	500 d	200 mm Sludge
4	2d section	Waste & drain	No	Hydrostatic	500 d	500 mm
5	1d column	Waste	Yes	Fixed moisture	1500 d	No
6	1d column	Waste	Yes	Fixed moisture	1500 d	700 mm
7	2d section	Waste	Yes, 6 cells	Hydrostatic	800 d	No

The examples can be run either:

- a. from existing input data files contained in project directories. The project directory name corresponding to each example is given at the start of each example chapter.

Or,

- b. 'from scratch', i.e. by preparing all input files

Consistent Units

Attention must be paid to the dimensions and units in which input parameters and data are specified.

The HBM engine is formulated for a combination of dimensions and units that meet the sometimes competing requirements of (1) a consistent set of SI units and (2) other reporting conventions, e.g. rainfall in mm/day.

Dimensions and accepted units used in the HBM model are summarised below.

Dimension	Unit	
Mass	Kilogram	kg
Length	Metres	m
Volume	cubic metre	m ⁻³
	Litre	l
Time	Second	s
	Day	d
Stress	Kilopascals	kPa
Unit weights	kilonewtons per cubic metre	kN.m ⁻³
Hydraulic conductivity	metres per second	m.s ⁻¹
Infiltration	millimetres per day	mm.day ⁻¹
Concentration	grams per cubic metre	g.m ⁻³
Mass conversion rates	grams per cubic metre per day	g.m ⁻³ .d ⁻¹
Diffusion coefficient	metres squared per day	m ² .d ⁻¹

Example 1: Two Dimensional Homogeneous Landfill Section

Project directory is Example1

This example introduces the operation and performance of the HBM model and GUI. It concerns the hydraulic, biodegradation and mechanical behaviour of a landfill cell. The unit section is rectangular in shape, 30m wide by 20m deep. Settlement of the landfill due to creep and biodegradation is observed over a period of 500 days. During this time, flow to, and discharge from, a sump at the bottom left corner of the section are also observed. All other boundaries are no flow boundaries. Decomposition is modelled as a function of the current biochemical, microbial and moisture conditions. The base of the section has a zero displacement condition assigned to it, whilst the sides of the section are constrained to move in the vertical direction only. Internal locations are free to displace in both x and y directions. The filling phase is not simulated, so neither self-weight nor applied loading are considered. In effect, this analysis depicts the idealised post-closure behaviour of a homogeneous landfill section that has been 'magicked' into place.

MODEL BUILDING - PREPROCESSOR

Entry to the Preprocessor is on the *General and Time* pane.

General data and time control

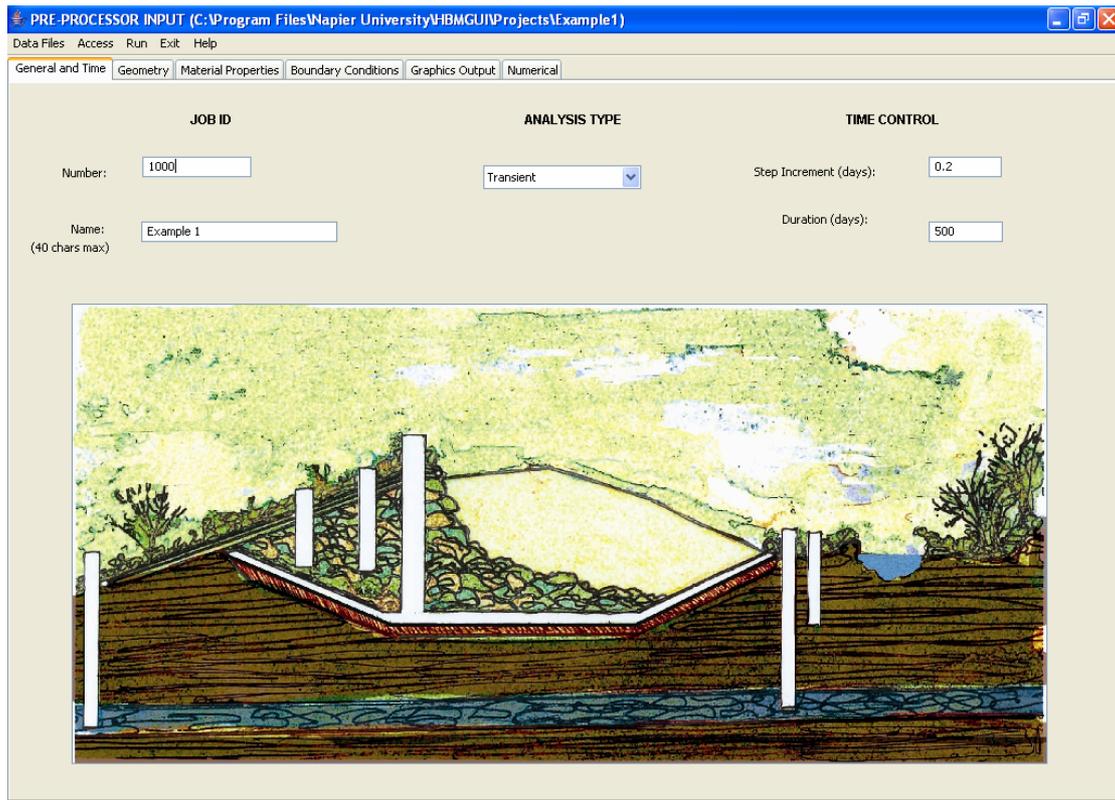
- ✦ Enter *Job number*.
- ✦ Enter *Job name*.

Assignment of the initial (as-placed) moisture content of the imported waste to each element, together with corresponding hydraulic pressure values, is done by the *Initialise Moisture* option, which instigates a steady state hydraulic analysis.

- ✦ Select *Initialise Moisture* in the *Analysis Type* option box.

The following two data inputs are only relevant to transient or time-dependent analyses. They are, however, data that are always read during run-time, hence it is necessary to provide input values.

- ✦ Enter *Time Step Increment* [days] = 0.2
- ✦ Enter *Duration* [days] = 1000.



Geometry

- ✦ Click on the *Geometry* pane tab.

If using pre-existing model data, the mesh geometry will be visible in the graphics pane on the right.

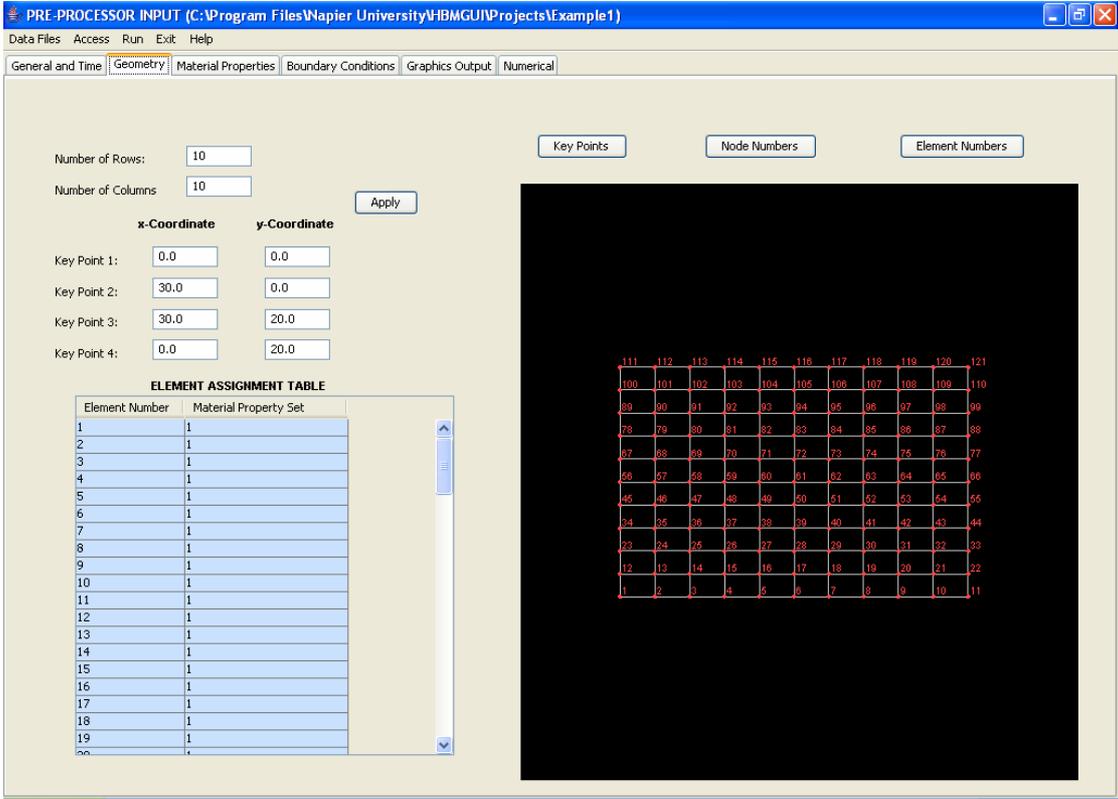
If building 'from scratch', then enter the following data.

- ✦ *Number of Rows = 10*
- ✦ *Number of Columns = 10*
- ✦ *Keypoint data - x & y coordinates (in metres):*

Keypoint	x	y
1	0.0	0.0
2	30.0	0.0
3	30.0	20.0
4	0.0	20.0

- ✦ Click *Apply*, to update the configured mesh.

The toggle switches above the graphics pane annotate the mesh with keypoint, node or element numbers.



Material Properties

- ✦ Click on *Material Properties* pane tab.

If building 'from scratch', add a material property set.

- ✦ Click on *Add Set*: A dialog box appears.
- ✦ Select the *Biodegradable* option, then click on *OK*.

A set of (biodegradable) material properties appears. Under *Basic* access (default), only the Initial Solid Decomposable Fraction and Bulk Unit Weight are defined. All other material property parameters are inactive (greyed out). The default parameters for the biodegradable waste material can be found in Appendix 1.

The top (gold shaded) row of the Material Property Set table contains the Material Property Set Number, which is used by the HBM model to identify the material property set¹.

- ✦ Check that the *Material Property Set Number* = 1
- ✦ Return to the Geometry pane to check that all elements in the Element Assignment Table are assigned the element material property set number, i.e. 1, in right hand column.

¹ The material property set number defaults to the lowest available number. Note however, that this number cannot be arbitrarily set because values of 4 or greater trigger infilling. See Theory Manual and Example 5 for more information on filling.

PRE-PROCESSOR INPUT (C:\Program Files\Napier University\HBMGUI\Projects\Example1)

Data Files Access Run Exit Help

General and Time Geometry Material Properties Boundary Conditions Graphics Output Numerical

MATERIAL PROPERTY SETS

Add Set Clear Set

System	Parameter	Unit	Value
Material Set	Material Property Set	#	1
Hydraulic	Van Genuchten Alpha	#	1.4
	Van Genuchten n	#	1.6
	Residual moisture content (w/w)	#	0.25
	Specific storage	#	0
	Vertical saturated hydraulic conductivity	m/sec	5.00E-5
	Ratio: vertical to horizontal conductivity	#	1
Biodegradation	Maximum hydrolysis rate	g/m3(aq)/day	2500
	Product inhibition factor	m3/g	2.00E-4
	Digestibility	#	0.7
	Half rate	g/m3	4000
	Methanogen growth	1/day	0.02
	Methanogen death	1/day	0.002
	Yield coefficient	#	0.08
	Diffusion coefficient	m2/day	0.05
	Initial solid degradable fraction	#	0.4
	Initial VFA concentration	g/m3	300
Initial methanogenic biomass concentration	g/m3	250	
Mechanical	Elastic stiffness	#	0.072
	Elastoplastic stiffness	#	0.23
	Poissons ratio	#	0.35
	Initial yield stress	kPa	30
	Creep viscosity	#	0.0015
	Decomposition-induced void change	#	-0.65
	Decomposition hardening	kPa	2
	Dry unit weight (as placed)	kN/m3	5
	Inert phase particle weight	kN/m3	17
	Degradable phase particle weight	kN/m3	7.3

Boundary Conditions

In this example, a hydrostatic moisture profile with a phreatic surface at the base is assumed. This is equivalent to the presence of a sump at the base of the landfill section.

Hydraulic

It is necessary to define a number of nodes, distributed over the problem domain, to guide the numerical solution. Since this is a hydrostatic analysis with a phreatic surface at the base, there will be a zero hydraulic pressure along the base and a negative hydraulic pressure (or suction) equal in magnitude to the elevation head at other locations in the problem domain. Here, nodes along the base and upper surface are assigned pressure heads of 0 and -20 kPa respectively.

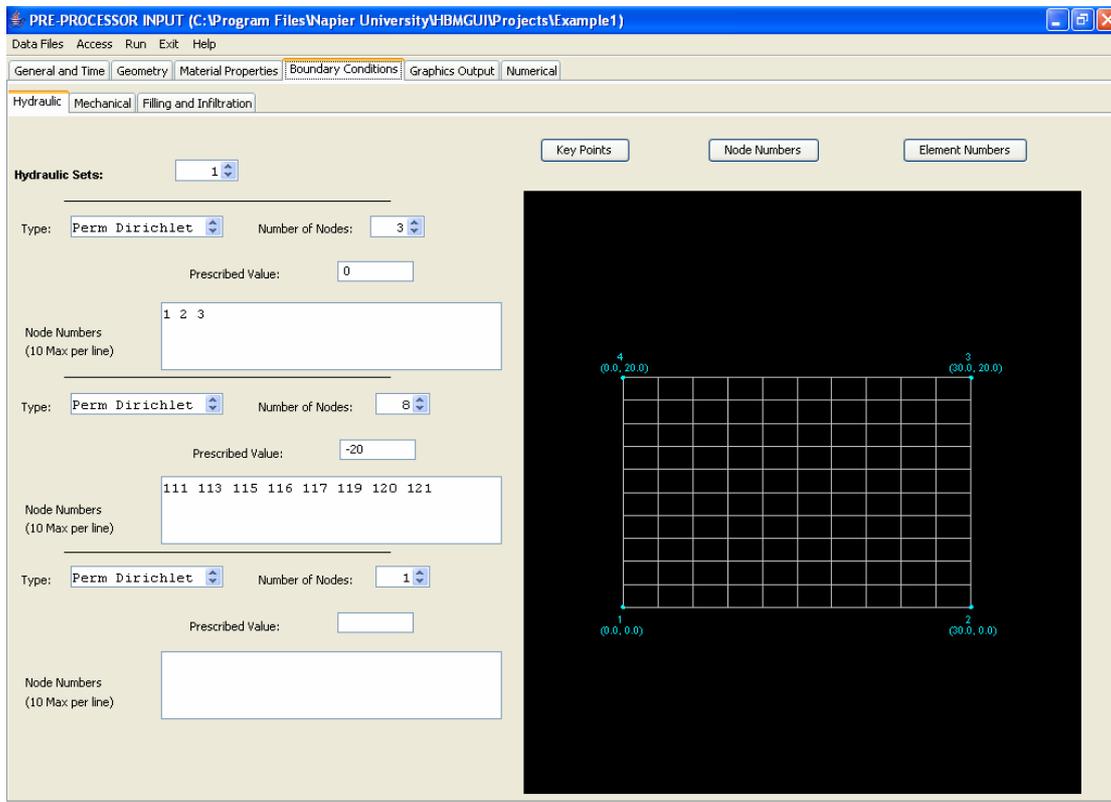
- ✦ From the *Boundary Conditions* pane, select the *Hydraulic* sub-pane
- ✦ Click on *Node Numbers* above the graphics pane to show necessary node number information
- ✦ Set *Hydraulic Sets* spinner box = 2.

For base hydraulic boundary conditions, in the first data group:

- ✦ Set *Type* spinner box to *Perm Dirichlet*
- ✦ Enter *Number Of Nodes* = 6
- ✦ Enter *Prescribed Value* = 0.0
- ✦ Enter *Node Numbers* = 1, 3, 5, 7, 9, 11. (No commas; each number separated by a space).

For upper surface hydraulic boundary conditions, in next data group:

- ✦ Set *Type* spinner box to *Perm Dirichlet*
- ✦ Enter *Number Of Nodes* = 6
- ✦ Enter *Prescribed Value* = -20.0
- ✦ Enter *Node Numbers* = 111, 113, 115, 117, 119, 121. (No commas; each number separated by a space).



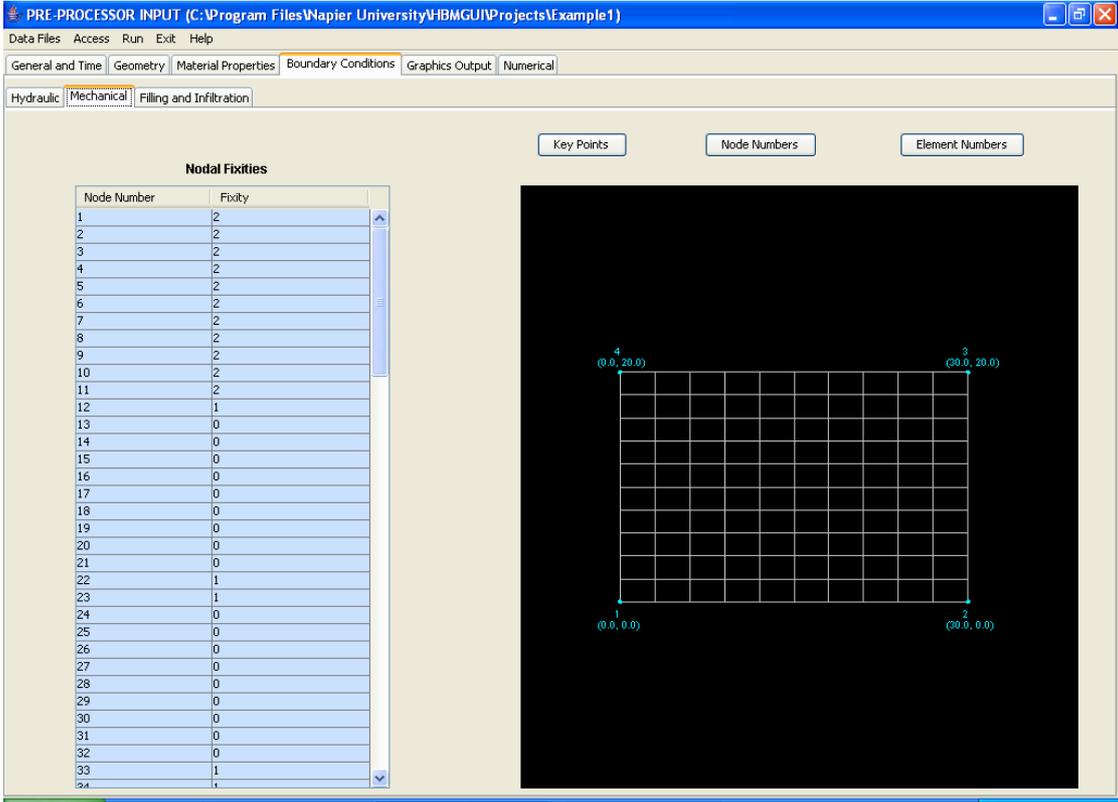
Mechanical

It is necessary to provide fixity (zero displacement) conditions. In this case, the base is fixed in both x and y directions (code = 2), the sides are fixed in the x-direction only (code = 1). All other nodes are free to move in both x and y directions.

- ✦ Enter into the *Nodal Fixities Table* the following codes. All other nodes are assigned a zero value, i.e. no fixity, by default.

Node	x&y fixity	Node	x&y fixity	Node	x&y fixity
1	2	12	1	67	1
2	2	22	1	77	1
3	2	23	1	78	1
4	2	33	1	88	1

5	2	34	1	89	1
6	2	44	1	99	1
7	2	45	1	100	1
8	2	55	1	110	1
9	2	56	1	111	1
10	2	66	1	121	1
11	2				



Infilling & Infiltration

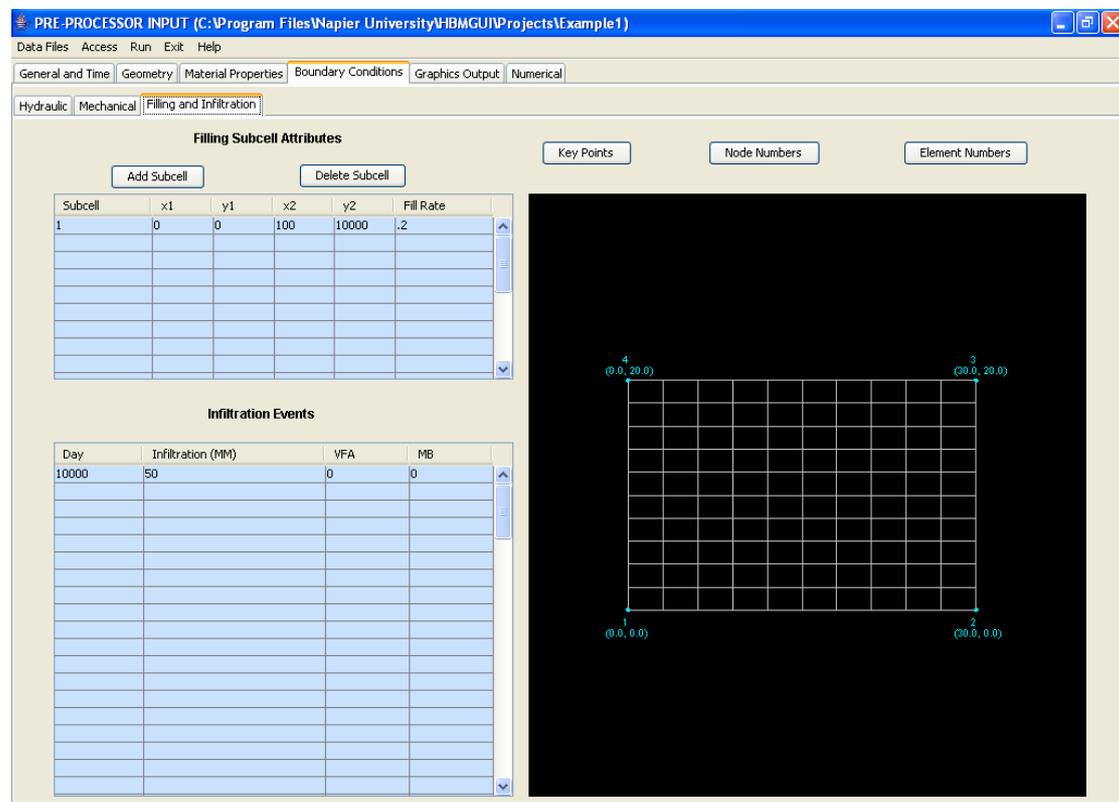
The HBM engine allows for the simulation of landfill operations such as infilling and moisture addition (either daily rainfall, raw water, sludge or recirculated leachate addition). The input of these conditions must be terminated with dummy variables to avoid end of file errors.

Since there is no filling in this example, we require only dummy input data in the filling table. Enter a nominal set of coordinates that comfortably exceeds the dimensions of the problem domain, and a filling rate (value is ignored for purposes of this example). For example,

- ✦ Enter in cells of the first row of the *Filling Subcell Table*,
- ✦ *Subcell* = 1; *x1* = 0.0; *y1* = 0.0; *x2* = 100.0; *y2* = 1000.0; *Fill Rate* = 0.2

A similar treatment is required for the Infiltration table.

- ✦ Enter in the cells of the first row of the *Infiltration Table*,
- ✦ *Day* = 10,000; *Infiltration* = 50; *VFA* = 0; *MB* = 0.



Graphics Output Control

Degradable content and other element properties are monitored in ten elements lying in a vertical line at the middle of the domain. Remember the node and element annotation buttons above the graphics viewing pane.

- ✦ Enter *Number Of Elements* = 10
- ✦ Enter *Elements* = 5, 15, 25, 35, 45, 55, 65, 75, 85, 95 (No commas)

Infiltration/discharge are monitored at two elements.

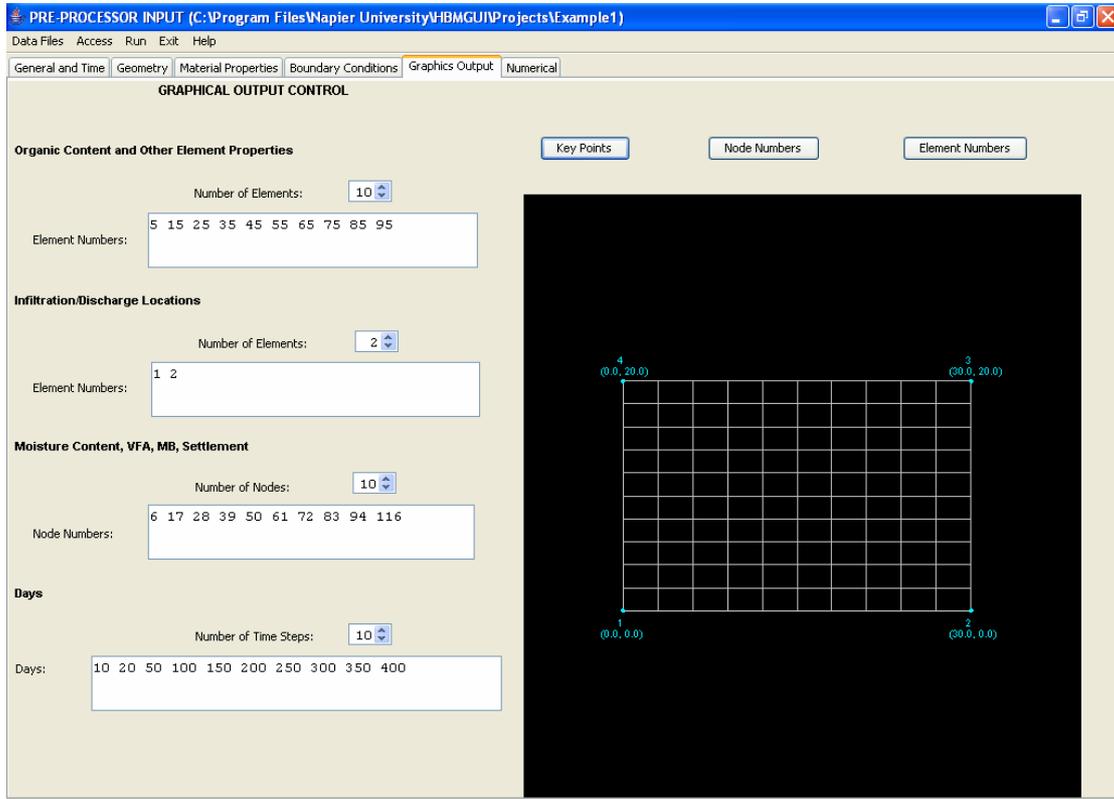
- ✦ Enter *Number of Elements* = 2
- ✦ Enter *Elements* = 1, 2 (No commas)

Moisture content, VFA, methanogenic biomass and settlement are monitored at ten nodes attached to the ten elements monitored for degradable content.

- ✦ Enter *Number of Nodes* = 10
- ✦ Enter *Nodes* = 6, 17, 28, 39, 50, 61, 72, 83, 94, 116 (No commas)

Element and nodal data items referred to above are monitored on (up to twelve) predetermined days. In this case 8 days are to be monitored:

- ✦ Enter *Number of Days* = 8
- ✦ Enter *Data days* = 5, 10, 20, 50, 100, 200, 300, 400 (No commas)



Saving the model and writing data files

The model is now ready to run. It is necessary to save the GUI data and create HBM input data files before running the model.

- ✦ From *Data Files* drop down menu, click on *Write Data*.

Note that there is no validation of input data. However, missing files and/or incorrectly formatted data should be captured by normal Fortran or Java run time error messages.

The prepared model must be saved and HBM input data files created by clicking on WRITE DATA before each solution.

SOLUTION

- ✦ From *Run* drop down menu, click on *Run Engine*

A dialog box appears.

- ✦ Click *OK* to confirm the run engine command.

A DOS window will be seen briefly, after which it is possible to proceed to the postprocessor. If hydraulic boundary conditions have been correctly specified, the HBM engine will find a solution to the initial moisture analysis very quickly.

INITIAL OUTPUT - POSTPROCESSOR

After an initialise moisture analysis only distribution profiles are available, i.e. output showing the deformed mesh and flow vectors, moisture and bulk properties.

To access the post processor,

- ✦ From drop-down *Run* menu, click on *Run Postprocessor*

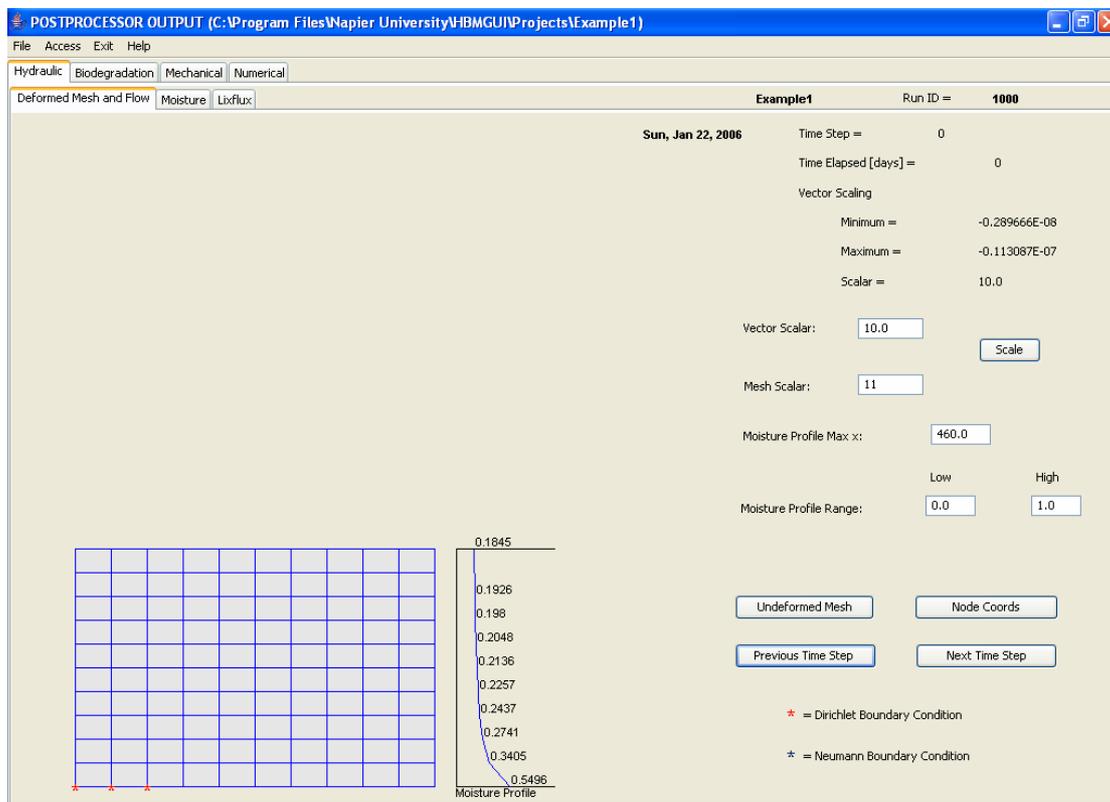
The postprocessor starts at the *Deformed Mesh & Flow* sub-pane of the *Hydraulics* pane

Deformed Mesh & Flow

To advance the view from the pre-trial (numerical) solution to the initial moisture contents.

- ✦ Click on *Next Time Step*

The moisture profile shown is that for the nodes defined under graphics output control. Default viewing pane scaling factors give the following view.



Bulk Properties

- ✦ Click on *Mechanical - Bulk Properties - Unit Weights & Saturated Hydraulic Conductivities* to view the initial bulk and dry unit weights and saturated hydraulic conductivity.

To return to the pre-processor and proceed to the time dependent analysis:

- ✦ From drop-down *Exit* menu, click on *Exit*.

Return to the pre-processor will be at the point of departure.

MODELLING TRANSIENT BEHAVIOUR - PREPROCESSOR

To investigate creep and biodegradation settlement behaviour over time, we remove the hydraulic boundary condition applied to the upper surface during the initialise moisture. The base conditions are modified to depict the leachate sump at the bottom left corner of the problem domain, i.e. nodes 1, 2 & 3. A zero hydraulic pressure, or phreatic surface, is maintained at these three sump nodes. All other boundaries are no flow boundaries.

The hydrostatic regime does not mean that there are no hydraulic effects. The simulation will show moisture redistribution due to compression and decomposition.

Boundary conditions

On *Boundary Condition* pane, *Hydraulic* sub-pane,

✦ Set *Hydraulic Sets* = 1

In the first set group

✦ Enter *Number of Nodes* = 3

✦ Enter *Node Numbers* = 1, 2, 3

General & Time

✦ From the *General & Time* pane, set the *Analysis Type* to *Transient*

Saving the model and writing data files

The model is now ready to run. It is necessary to save the GUI data and create HBM input data files before running the model.

✦ From *Data Files* drop down menu, click on *Write Data*.

Note that there is no validation of input data. However, missing files and/or incorrectly formatted data should be captured by normal Fortran or Java run time error messages.

The prepared model must be saved and HBM input data files created by clicking on WRITE DATA before each solution.

SOLUTION

- ✦ From *Run* drop down menu, click on *Run Engine*

A dialog box appears.

- ✦ Click *OK* to confirm the run engine command.

A DOS window appears and shows some run time information. The runtime information continues to scroll as the solution advances. A runtime error will result in an error message to the screen or the runtime information hanging.

The simulation, which took about 15 minutes to run on a Pentium P4 2.8 GHz machine, will return to the departure point in the preprocessor.

OUTPUT - POSTPROCESSOR

- ✦ From the drop-down *Run* menu, click on *Run Postprocessor*.

Hydraulic

Deformed mesh & flow

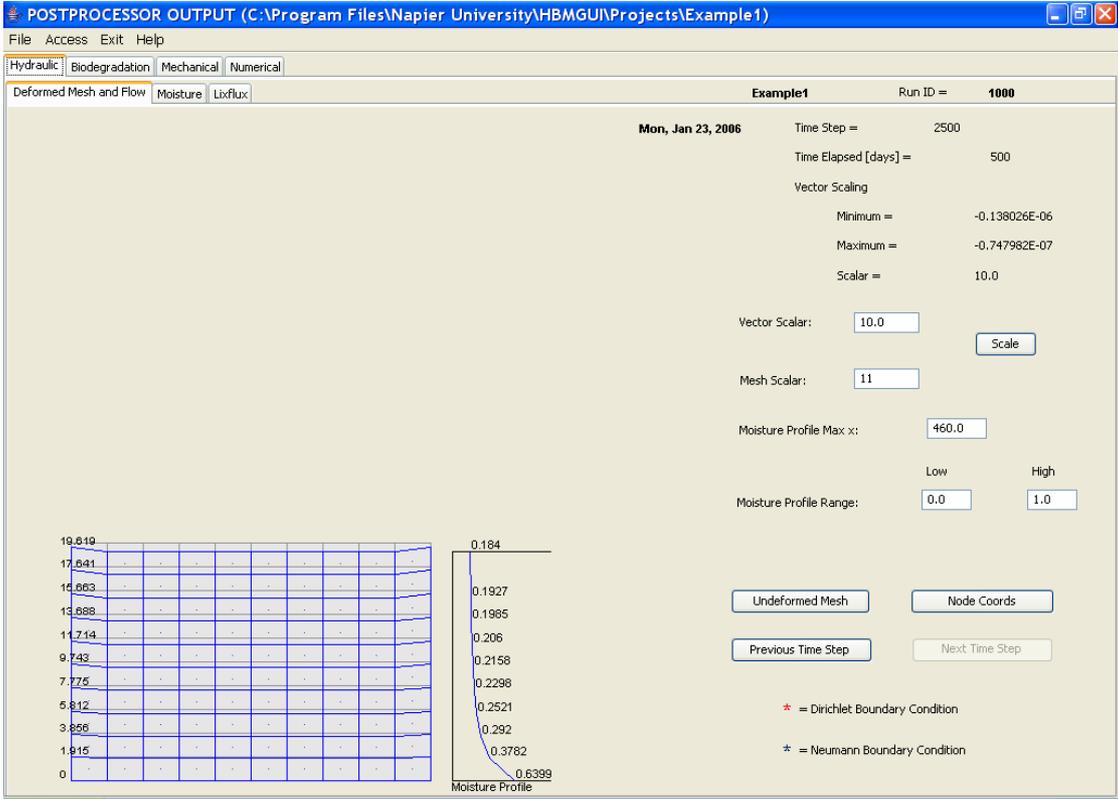
The deformed mesh and flow vector sub-pane shows the problem domain with hydraulic boundary conditions at the start of the analysis, i.e. time step = 0. This view provides a check on the initial hydraulic regime and boundary conditions. Flow vectors are not shown at this time step.

The deformed mesh, flow vectors (at time steps > 0) and moisture profiles can be resized using the vector, mesh and range scaling factors. The *Mesh Scalar* default is 11 and *Vector Scalar* default is 10; for improved readability of the moisture plot:

- ✦ Set the *Moisture Profile Range*, *Low* = 0.1 and *High* = 0.7
- ✦ Click on the *Scale* button

In this example, the absence of any boundary flux results in very low seepage fluxes and hence small vectors. However, mesh displacement and changing moisture profiles can be seen using the next/previous time step buttons.

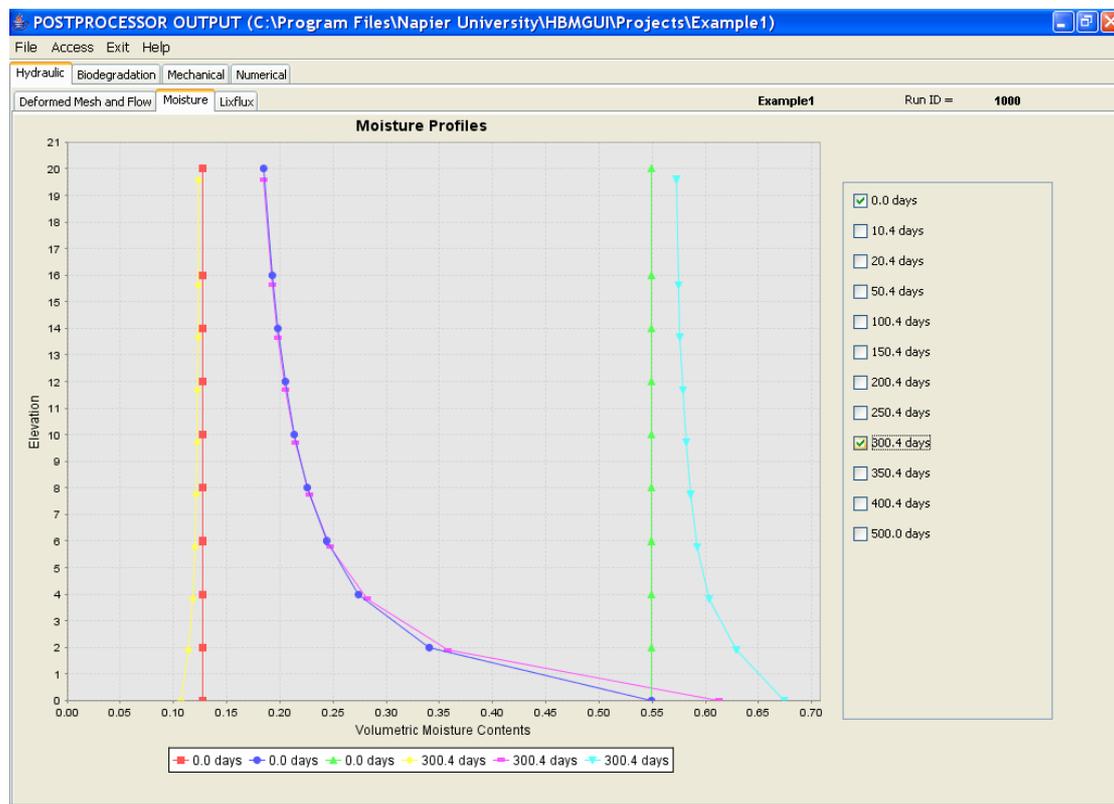
The deformed mesh and moisture profile for day 500, with vector scalar = 10, undeformed mesh and nodal coordinates turned on, should look like this:



Moisture

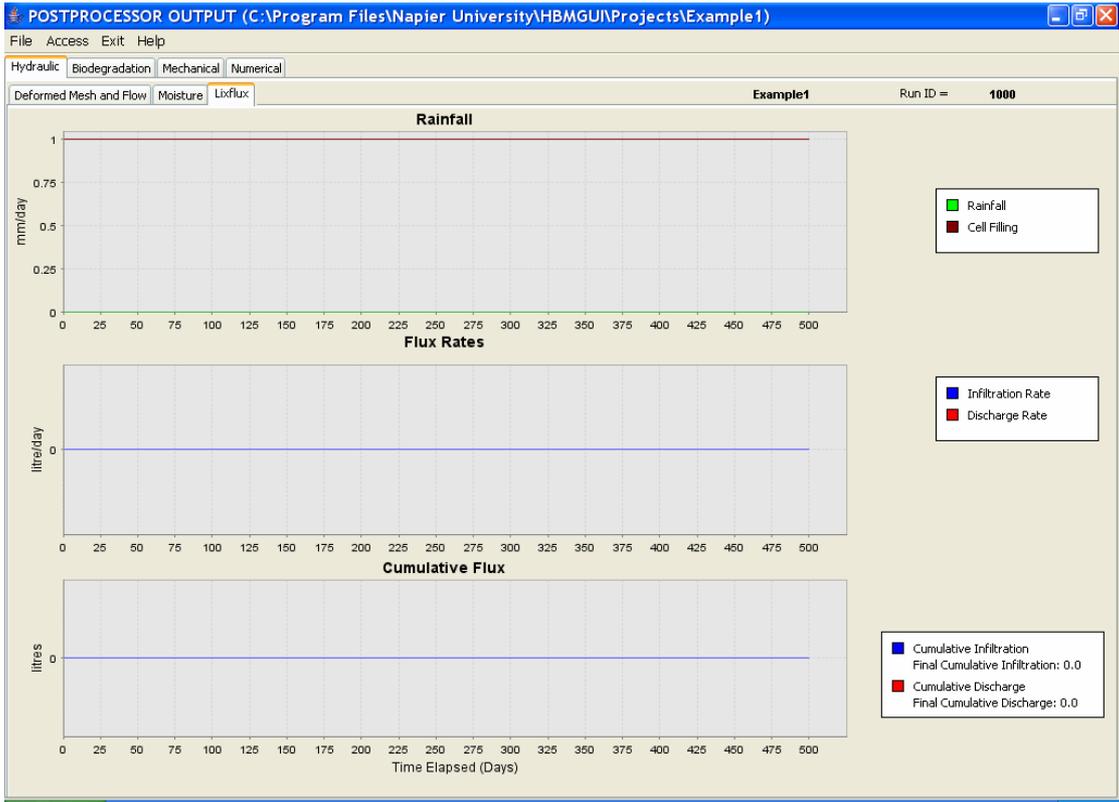
Moisture content profiles, residual (left), actual (middle) and saturated (right), can be viewed for any combination of times during the simulation by selecting the appropriate boxes on the right of the pane. The view shown here is for the initial conditions and those at 300 days.

It is interesting to note the increase in saturated moisture content (porosity) and reduction in residual moisture content indicated by the model. These phase changes are consistent with the loss of solid matter under a decomposition-induced void volume change parameter of -0.65 and variations in moisture content.



Lixflux

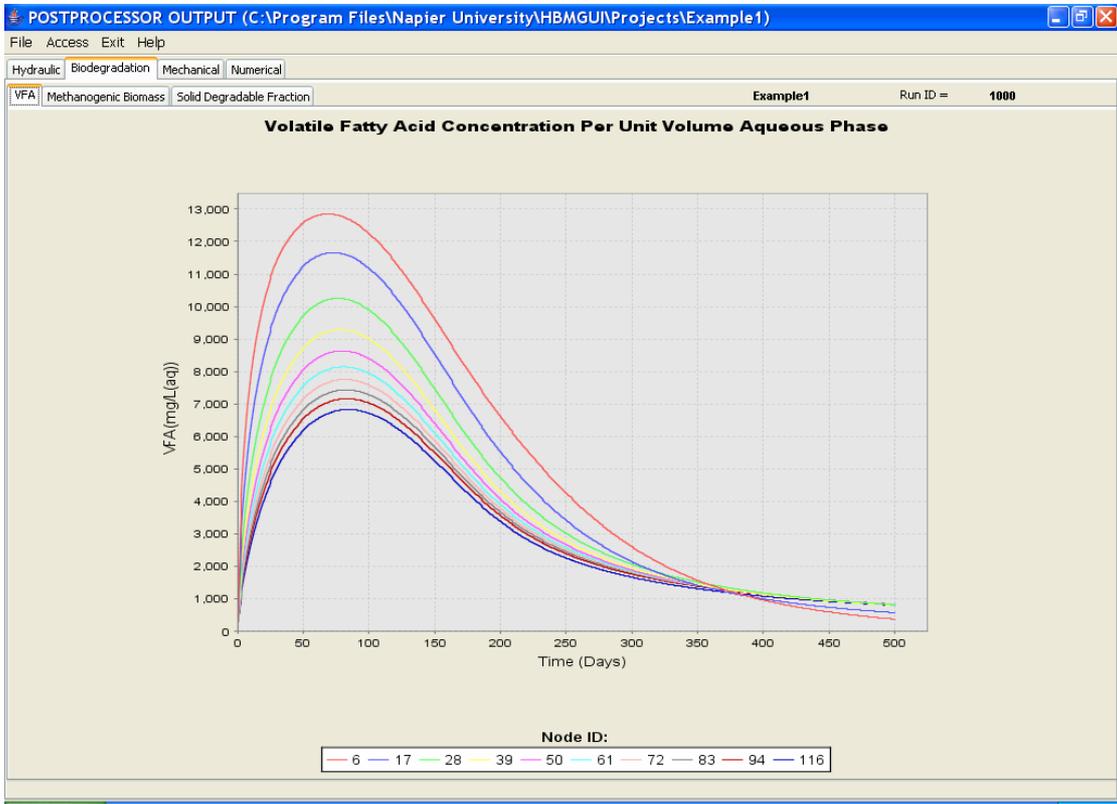
As indicated by the deficit of the actual moisture content relative to the saturated moisture content at the base of the site, flux plots report no discharge from this section.



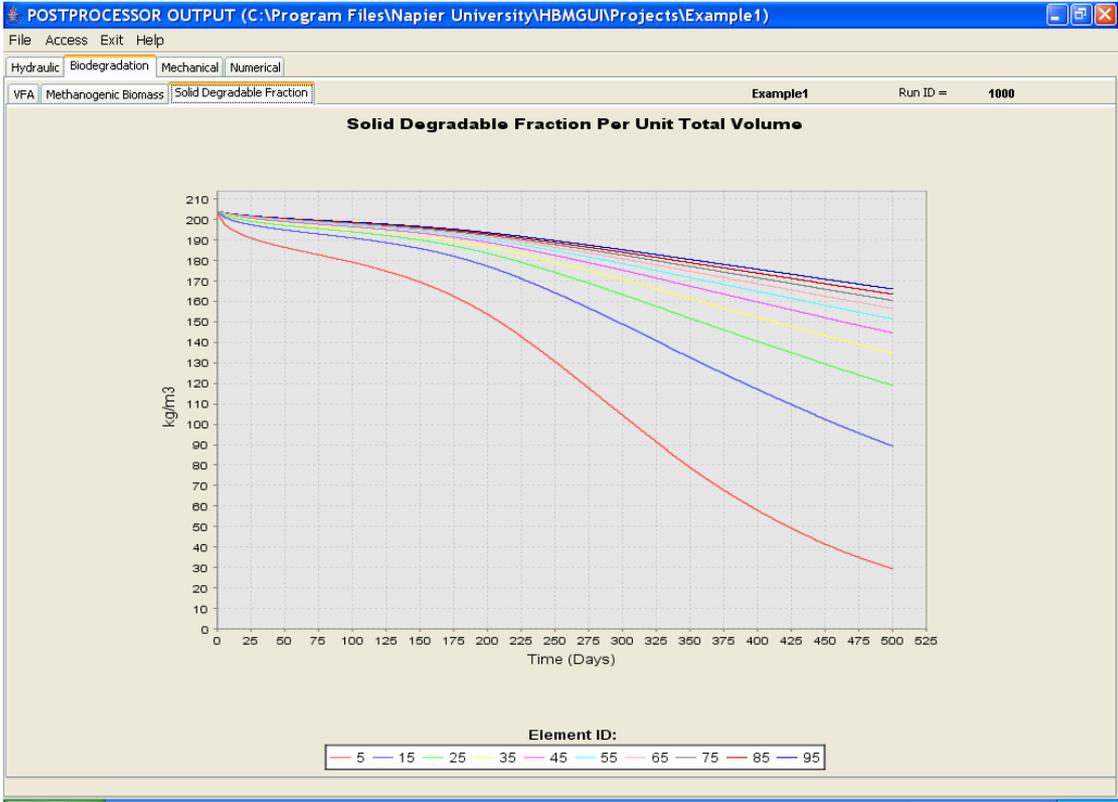
Biodegradation

Evolution of VFA and methanogenic biomass over time is shown in the sub-panes of the Biodegradation pane

Volatile fatty acids show a characteristic rapid rise in the early stages of decomposition, whilst methanogenic biomass accumulates rather more slowly.



Solid degradable fractions show the pronounced influence of moisture on biodegradation in the elements at lower elevations.

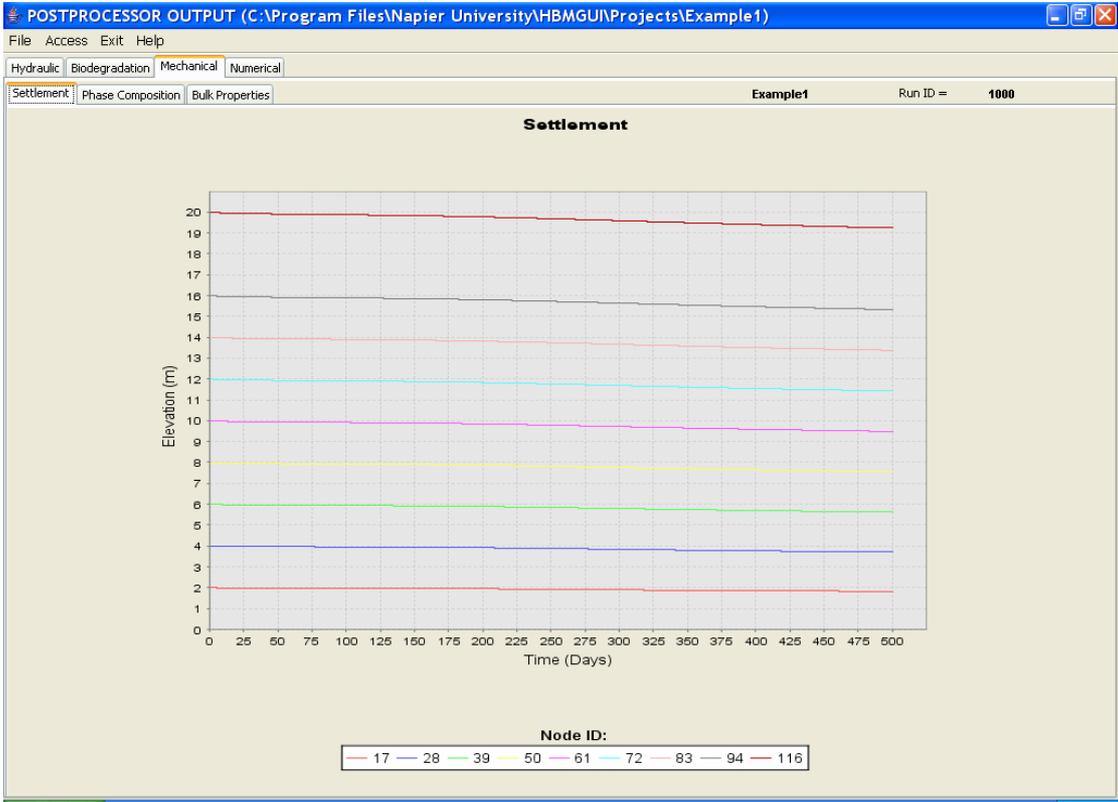


N.B. Zooming in on graphs, such as those above, done by click and drag operations. More precise rescaling can be performed using right mouse-button functions.

Mechanical

Settlement

Settlement of the ten specified nodes is shown as elevation over time. At the surface, settlements are about 0.76m. Note that this settlement figure is highlighted as a reference for later simulations, rather than as a validated quantitative prediction.

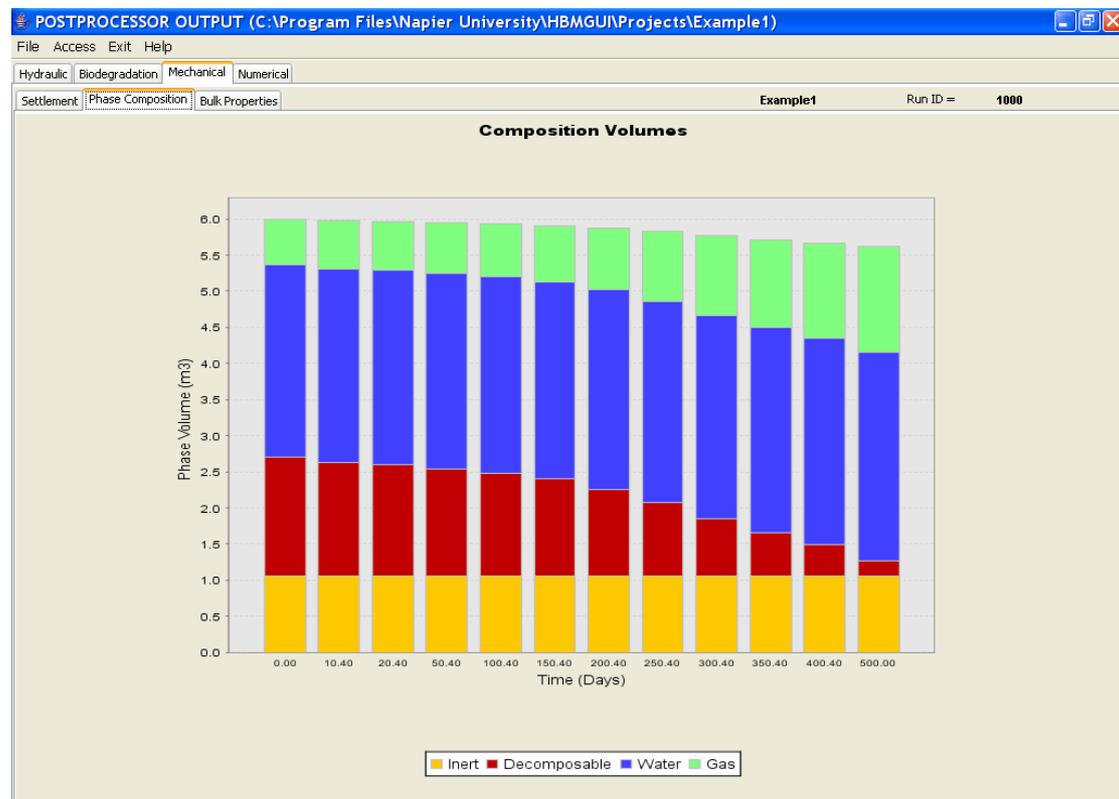


Phase composition

Phase compositions relate to element 1 and for time steps specified in Graphics Output Control. In contrast to a conventional geotechnical soil model, the phase composition here describes a four-phase material. It should be noted that there is:

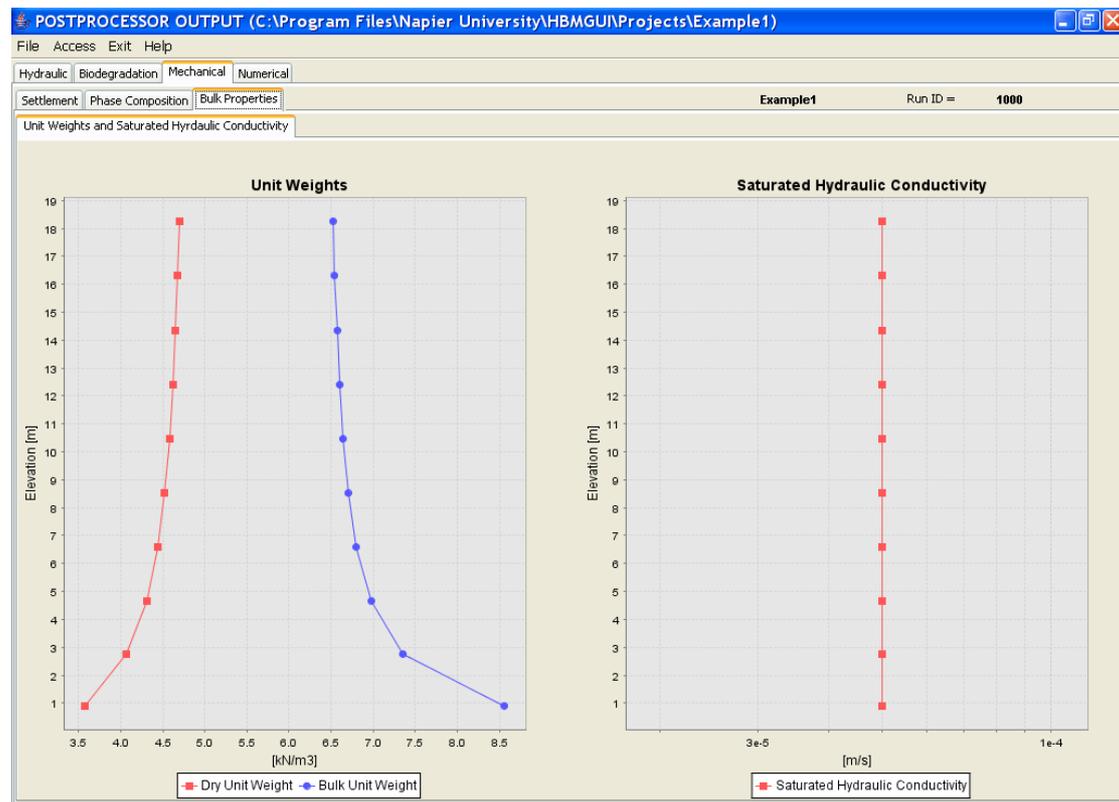
- no change in solid inert volume,
- decomposable volume is removed by biodegradation,
- although loss of decomposable volume induces a change in void volume, reductions in void volume are also caused by mechanical creep, and
- moisture volume is determined by the unsaturated flow analysis with moisture retention parameters dependent on phase composition.

Note also that individual phase volume quantities can be obtained by placing the mouse cursor over the relevant part of the phase diagram.



Bulk Properties – Unit Weights & Saturated Hydraulic Conductivity

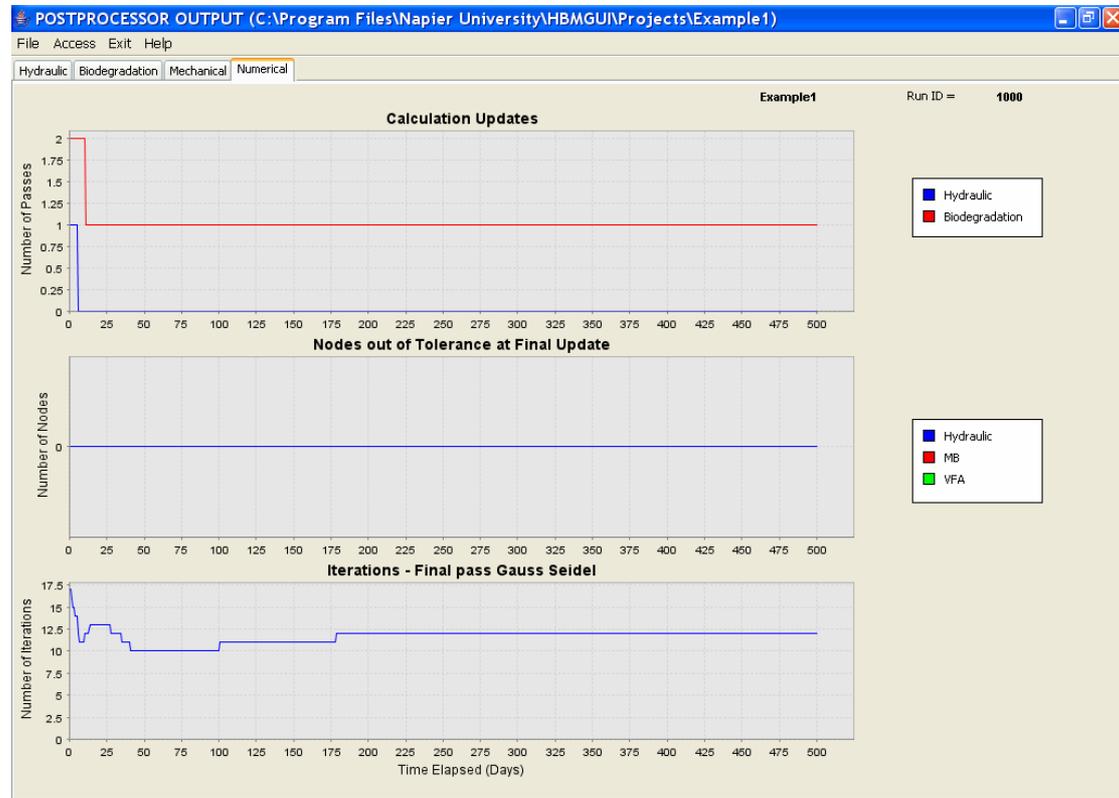
This pane shows two plots: (i) the variation of bulk and dry unit weights with depth and (ii) saturated hydraulic conductivity with depth. Both diagrams report data taken from the specified graphics output elements and plotted on the vertical axis as the elevation of the midpoint of the element. The influence of biodegradation is again evident in the dry unit weight profile. Dry density has reduced and void volumes increased by decomposition throughout the profile but particularly so at the base of the section. Bulk unit weight shows the additional mass of retained moisture. The constant saturated hydraulic conductivity is evident in the right-hand diagram.



Numerical

This pane reveals the numerical performance of the simulation, which offers an insight into the validity of the solution. In this case the numerical solution data indicate a comfortably obtained solution.

Ideally, there should be no nodes out of tolerance, the number of updates required by the solution, and the number of iterations in the final pass through the iterative solver should be 'low'. Of course the definition of low is not easy and the relationship of the variables in question with the solution is not simple. Nevertheless, such characteristics indicate that a solution has been comfortably obtained. If the number of nodes out of tolerance is high or becomes unstable, and the instability is not associated with a boundary condition perturbation, then the solution should be investigated – typically by sensitivity of the solution to the numerical parameters, especially the time step. It is widely recognised that the accuracy of numerical solution schemes is related to time step and mesh discretisation size.



Exit

- ✦ Click on *Exit* to close the Postprocessor
- ✦ Click on *Exit* to close the Preprocessor

EVALUATING THE SIMULATION

Hydraulic Mass Balance

Hydraulic mass balance is a function of compression, moisture retention and metabolic consumption of moisture, the combined outcome of which is predicted to be no discharge. Some of these factors can be easily checked.

Compression. Surface settlement is approximately 0.76 m over the greater part of the 30 m wide section. Volumetric moisture contents in the upper element of the uncompressed section are 0.1845, which means that after compression, the section is required to receive an additional 4.2 m³ of moisture². Since the initial condition is hydrostatic, then, notwithstanding changes in phase composition and retention properties, an additional 4.2 m³ of moisture would need to be accommodated by the compressed section.

Decomposition. The simulation indicates a significant volume of decomposition – about 46,000 kg of degradable matter³. Given that 1 mole of cellulose (162 g) requires to be hydrolysed by 1 mole of water (18 g), the decomposition of 1 kg of cellulolytic matter requires 111g (0.111x10⁻³ m³) of water. This corresponds to 5.06 m³ of water for the whole section⁴. On the calculations presented here, the predicted amount of cellulolytic hydrolysis requires more moisture than that which would be excess to the hydrostatic condition in the compressed section, hence no discharge would be expected.

In contrast, changes in moisture retention properties are likely to occur with changes in phase composition but these are more difficult to quantify.

² 0.76 m x 30 m x 0.1845 = 4.2 m³

³ Initial SDF = 30 m x 20 m x 203.87 kg/m³ = 122322 kg
 From SDF output data, SDF remaining at 500 days = 76364 kg
 SDF converted over 500 days = 122322 – 76364 = 45958 kg

⁴ 46,000 kg x 0.111x10⁻³ m³/kg = 5.06 m³

Example 2: Two Dimensional Homogeneous Landfill Section with Raw Water Addition

Project Directory is Example2

This example builds on Example 1 by the inclusion of an infiltration event – 50 mm/day for a period of 10 days, days 50 – 59 inclusive, which is applied to the upper surface. Since this infiltration event is a known or prescribed flux, it is a Neumann boundary condition.

The impact of the infiltration event will be followed through the postprocessor, particularly in the flow vectors on the deformed mesh and the infiltration/discharge pane.

The infiltration event is controlled by revised entries in the *Hydraulic* and *Infiltration* sub-panes of *Boundary Condition* pane. First, however, if the previous job is to be saved, it is necessary to create a new project directory.

To Start the New Example

- ✦ Start the GUI using the desktop icon.

From the Open Project file chooser, a number of options exist. This example can be:

- a) Built from scratch following the input instructions of Example 1 and the additional model building described below. Open a new project directory
- b) As an extension to Example 1, whereby only the additional model building described below is undertaken. Open *Example1* (or your previously defined project name).
- c) By following a previously built model. Open *Example2*.

MODEL BUILDING - PREPROCESSOR

The model and initial hydraulic conditions of Example 1 are used here so there is no need to repeat the initial moisture analysis.

To fully define an infiltration event, we must specify the location of the boundary flux, its magnitude and timing. The location and initial magnitude are entered via the hydraulic boundary condition pane. The timing and magnitude of the full sequence of infiltration events are entered via the infiltration table.

Go directly to the hydraulic boundary conditions pane.

Boundary Conditions

Hydraulic

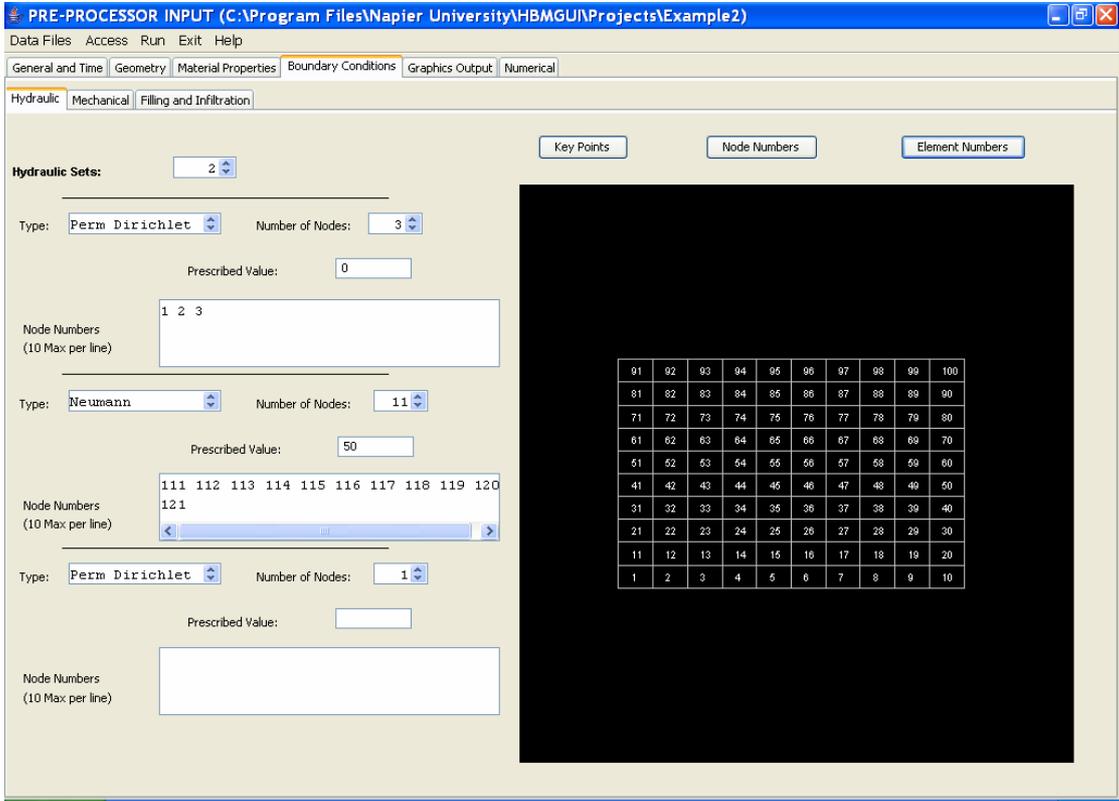
In Hydraulics sub-pane:

- ✦ Set *Hydraulic Sets* = 2

In the second set group,

- ✦ Set *Type* spinner box to *Neumann*
- ✦ Enter *Number Of Nodes* = 11
- ✦ Enter *Prescribed Value* = 50 (mm/day)
- ✦ Enter *Node Numbers* = 111 112 113 114 115 116 117 118 119 120 on one line.
- ✦ Press *Enter*, and then
- ✦ Enter 121 on the next line.

The hydraulic pane should now look like this:



Infiltration & Infilling

Enter infiltration events as daily events in columns 1 & 2 of the Infiltration Table. Influent water quality characteristics in the form of VFA and MB concentrations are entered in columns 3 & 4. For the case of raw water, set VFA = 0 and MB = 0.

✦ Complete the infiltration table as follows:

Day	Infiltration (mm)	VFA	MB
50	50	0	0
51	50	0	0
...
58	50	0	0

59	50	0	0
10000	50	0	0

N.B. Dummy termination data is required to avoid end of file errors.

Graphics Output Control

Output data is modified to extract flow vector and other data around the time of the infiltration event.

- ✦ Enter *Number of Days* = 11
- ✦ Set *Data Days* = 20, 49, 51, 54, 59, 75, 100, 150, 200, 300, 400 (No commas)

Saving the model and writing data files

The model is now ready to run. It is necessary to save the GUI data and create HBM input data files before running the model.

- ✦ From *Data Files* drop down menu, click on *Write Data*.

Note that there is no validation of input data. However, missing files and/or incorrectly formatted data should be captured by normal Fortran or Java run time error messages.

<p>The prepared model must be saved and HBM input data files created by clicking on WRITE DATA before each solution.</p>

SOLUTION

- ✦ From *Run* drop down menu, click on *Run Engine*
- ✦ Click *OK* to confirm the run engine command.

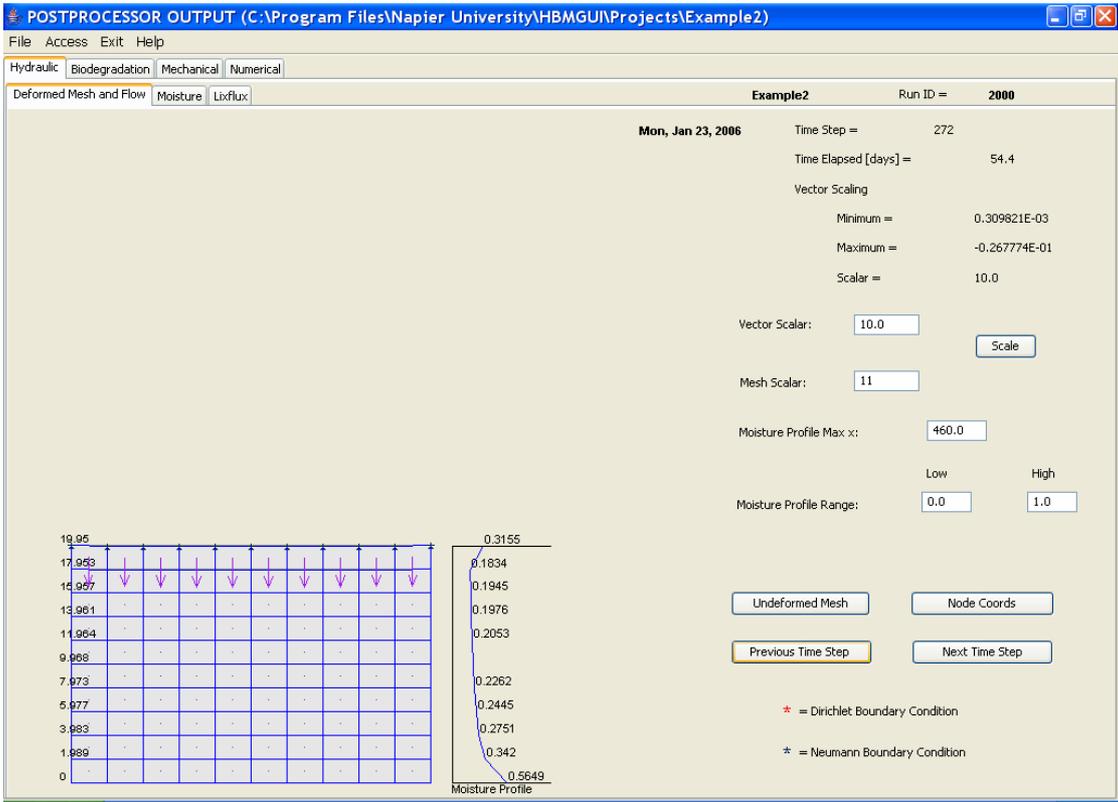
OUTPUT - POSTPROCESSOR

✦ From the Run drop down menu, click on *Run Post Processor*.

Hydraulic

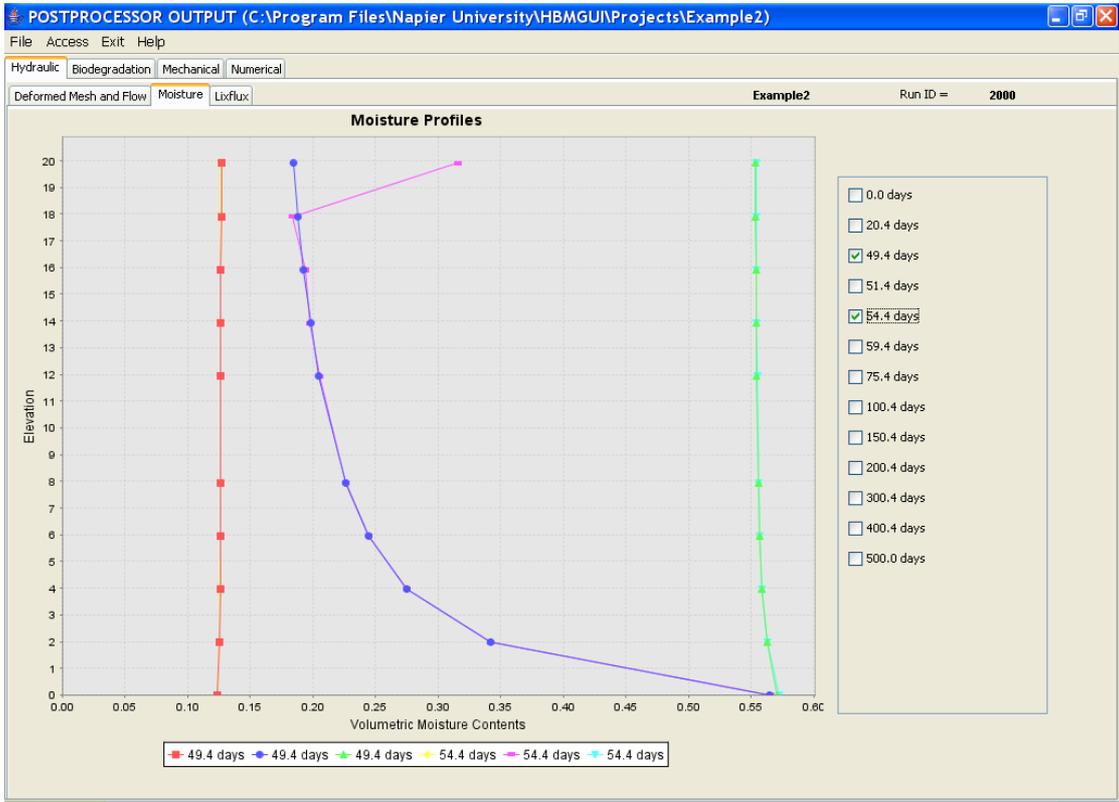
Deformed Mesh & Flow

As in the previous example, a sequence of flow vector plots is obtained using the *Next* and *Previous Time Step* buttons. The infiltration event is clearly shown in the flow vector plot for days 51, 54 and 59.



Moisture

By selecting appropriate time steps it is possible to explore the change in residual, saturated and actual moisture contents. In this case it is interesting to compare the moisture profiles on days 49 and 59. The infiltration event is evident from the increase in moisture content in the upper part of the profile.

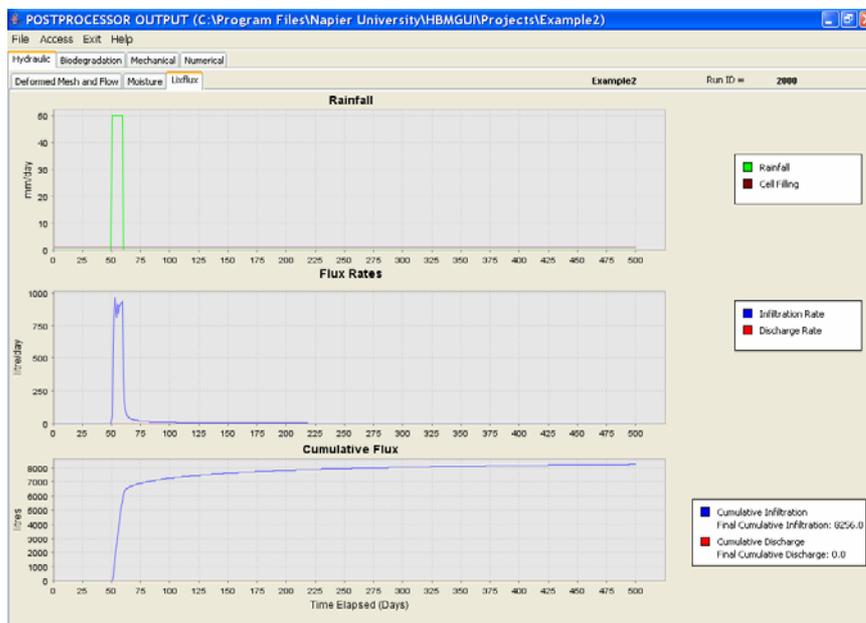


Lixflux

The rainfall event is evident in the upper plot. Since the upper surface of the model is 30 m wide and subject to an infiltration rate of 50 mm/day, the infiltration rate is 1500 litres/day. However, the flux rate plot (centre pane) shows a rather erratic infiltration rate of around 900 litres/day. Furthermore, cumulative infiltration shown in the bottom plot, rises to only 8256 litres, whereas the prescribed cumulative infiltration is 15,000 litres⁵. The issues of mass balance and reported fluxes are examined more closely in the section on *Assessing Simulation Output Data*.

There is no reported discharge in this scenario. This may be attributable to the low hydraulic conductivity that has stopped the infiltrative flux reaching the base of the section, from where it could discharge to the sump.

Discharge fluxes are, however, more difficult to determine when the flow field around the discharge point is two dimensional, as is the case here. Further details on the verification of mass balance in the hydraulic model, including the validity of flux monitoring, can be found in McDougall (1996).

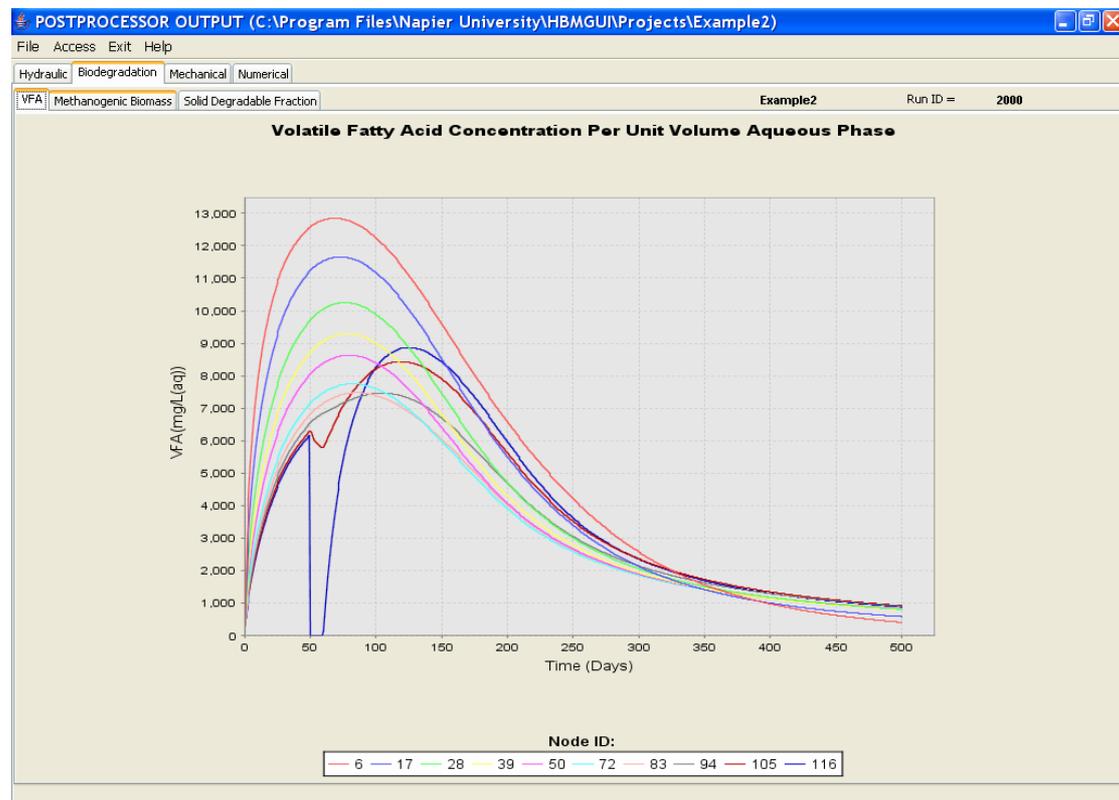


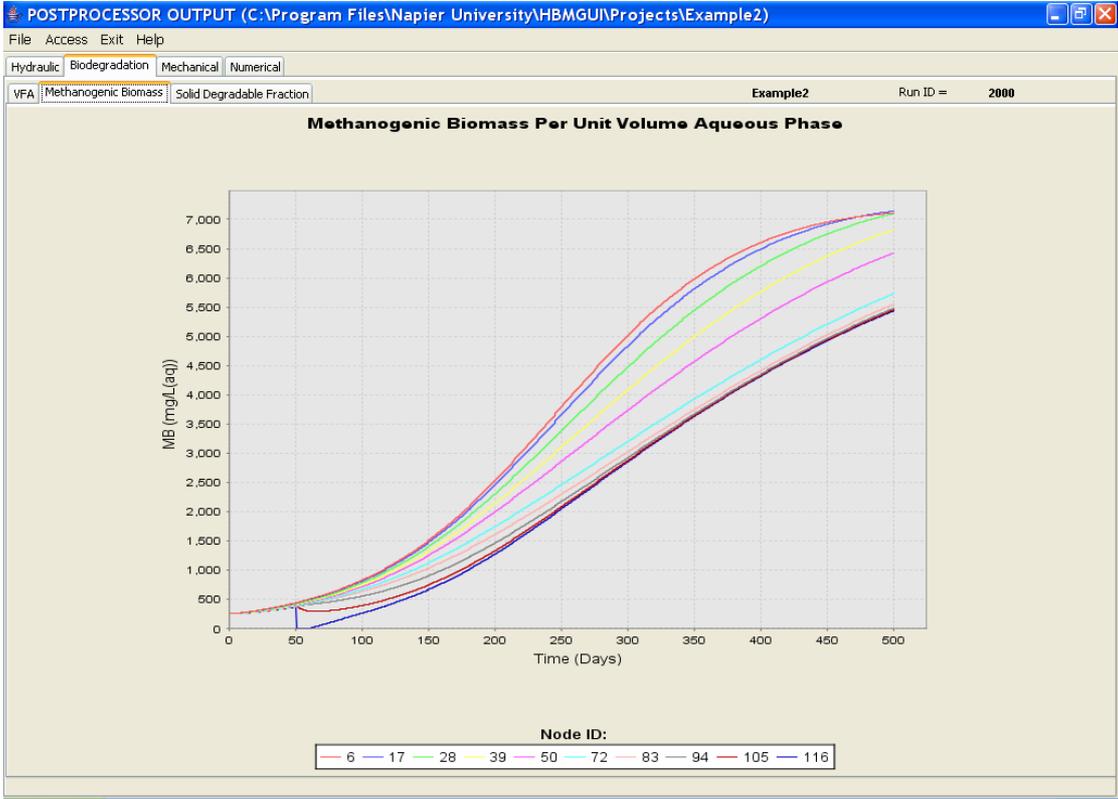
⁵ 15,000 litres = 1500 litres/day x 10 days

Biodegradation

VFA & Methanogenic Biomass

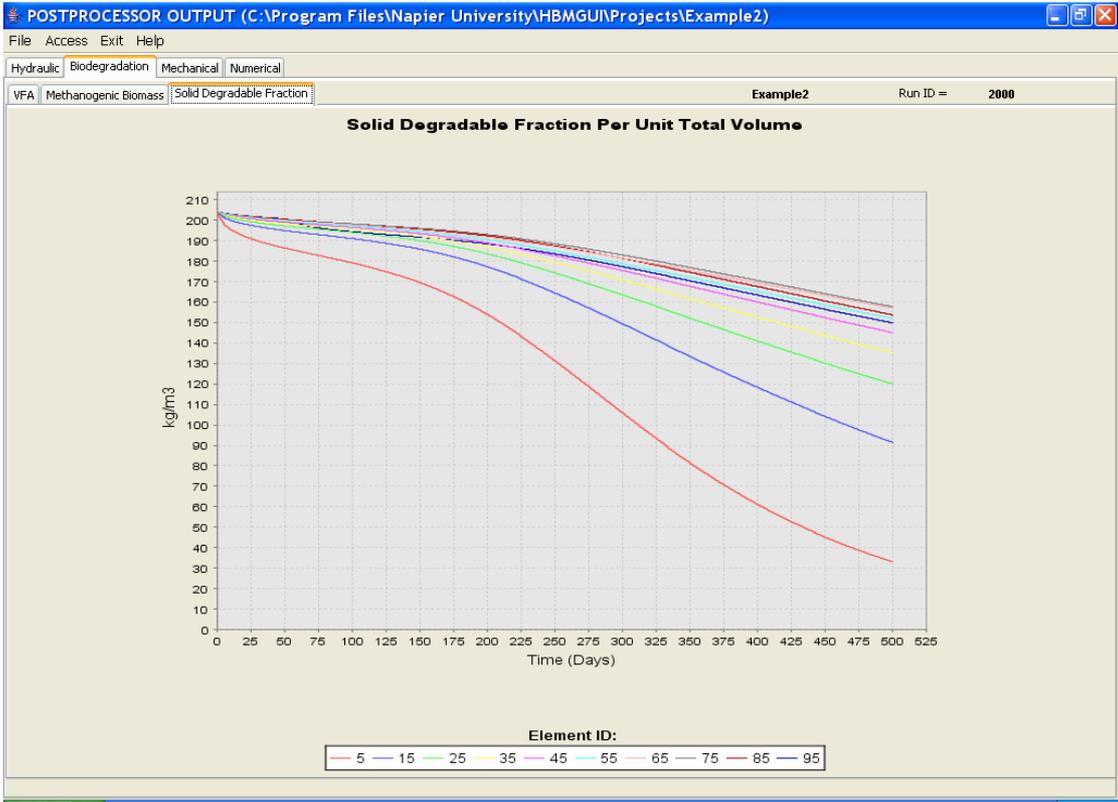
The infiltration of raw water is evident in the VFA plots. This is particularly so at node 116 on the upper surface, where VFA concentration immediately drops to zero due to raw water ingress. Interestingly, the reduction in VFA concentration extends only a short distance into the section. This is because there is a rapid enzymatic hydrolysis of cellulose to VFA in the plume of raw water and VFA concentrations rapidly rise. It may be noted, however, that the new levels are higher than those obtaining prior to the infiltration event. This is due to lower methanogen population. Methanogenic biomass accumulates more slowly than VFA so methanogenesis more slowly than prior to flushing; VFA concentrations thus rise higher, at least until methanogen levels are restored.





Solid decomposable fraction

The impact of raw water flushing is also evident in decomposition of element 95. A reduction in the decomposable fraction has been triggered by the raw water ingress through this element.



Mechanical

Settlement

Settlement, due to both creep and decomposition, at various locations within the section are shown in the settlement plot. The upper surface shows a settlement of about 0.78 m over the 500 days of the simulation.

Phase composition

The change in phase composition for element 1 can be followed in the phase composition pane. Remember that individual phase volumes can be revealed by placing the mouse cursor over the corresponding part of the phase diagram.

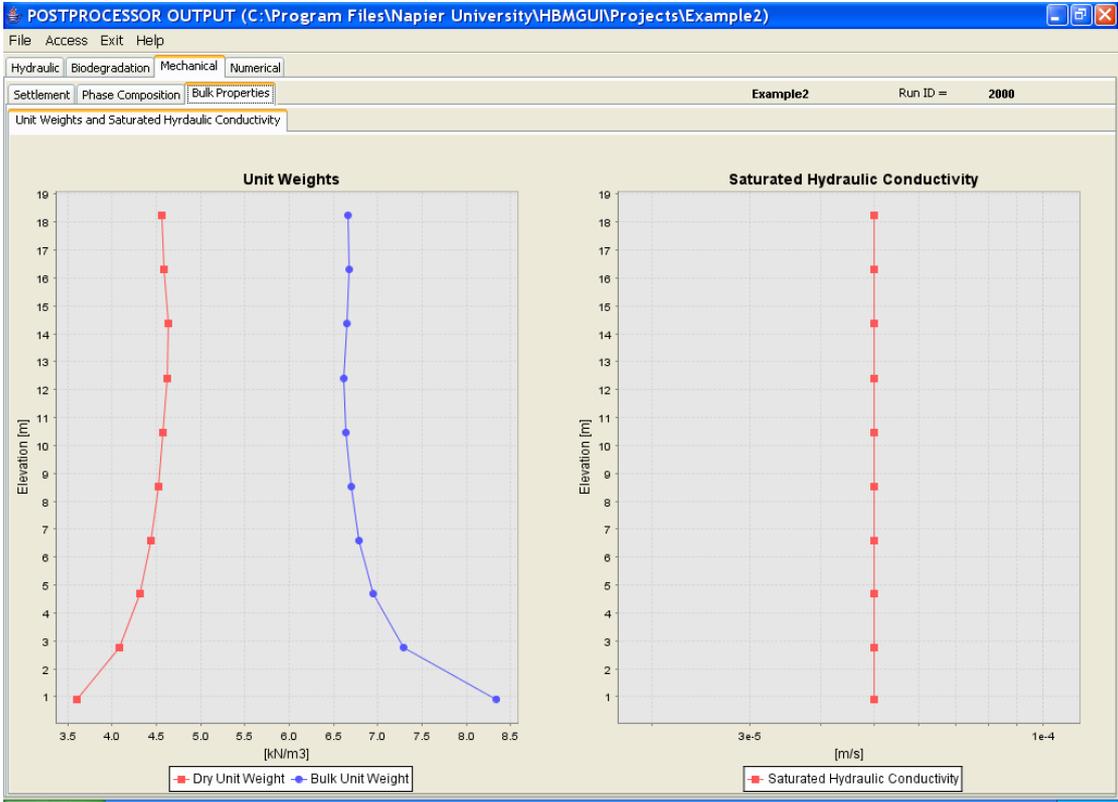
Bulk Properties – Unit Weights

Clearly there has been decomposition of the section throughout its depth. The dry unit weight profile for the section varies unusually from about 4.6 kN/m³ at the top, to 3.6 kN/m³ at the base – rather lower than the initial 5 kN/m³. Changes in the base element can be explored using the volumetric data available by placing the mouse cursor over the relevant phase components on the phase composition sub-pane. Certainly, the lower unit weight in the base element is attributable to greater decomposition (due to higher moisture content). However, the reduction in unit weight here is rather less than the increase in void ratio from, 1.22 to 3.32, would suggest. This is explainable by the relatively low particle weight, 7.3 kN/m³ of degraded solid matter, and the high particle weight, 17 kN/m³ of the remnant phase. The much heavier remnant solid phase works to increase unit weight whereas the increase in void ratio, due to $\Lambda = -0.65$, reduces it; the combination of these influences is a small decrease in dry unit weight.

Phase volume	0 days	500 days
Gas	0.627	1.587
Moisture	2.67	2.734
Solid decomposable	1.644	0.244
Solid inert	1.059	1.059

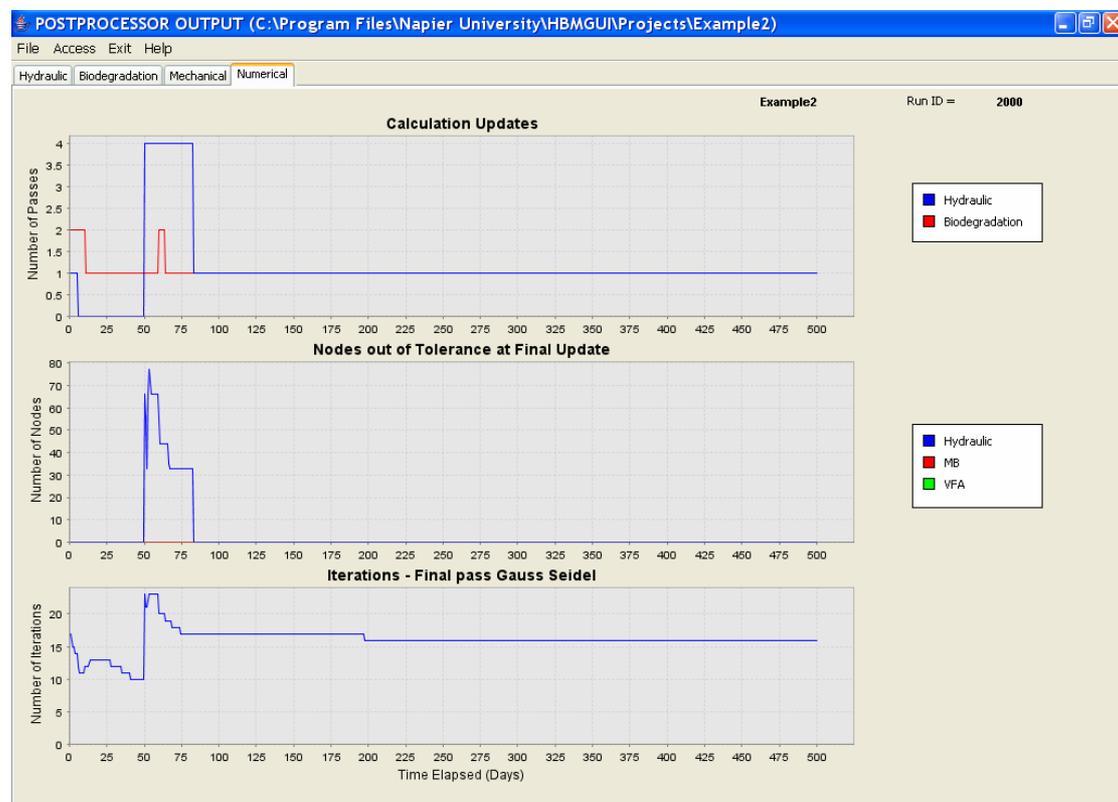
Void ratio	1.22	3.32
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There is also a lower dry unit weight at the upper surface. This is likely to be triggered by the low hydraulic conductivity and trapped infiltration that has encouraged decomposition at that level.



Numerical

The numerical output data clearly reflects the infiltration event. The perturbation has increased both the number of solution updates required and the number of nodes out of tolerance in the hydraulic system until about 15 days after the event. The solution process appears to be stable.



Exit

- ✦ Click on *Exit* to close the Postprocessor
- ✦ Click on *Exit* to close the Preprocessor

EVALUATING THE SIMULATION

Hydraulic Mass Balance & Accuracy of Reported Fluxes

The 30 m section and prescribed infiltrative flux correspond to an infiltration rate of 1,500 mm/day and cumulative infiltration of 15,000 litres. This example indicates zero discharge and a general settlement (away from edges) of 0.76 m. Both degradable fraction depletion (66900 kg) and moisture retained (149.02 m³) at the end of the simulation are only a little higher than Example 1 so it is surprising that no discharge is predicted, i.e. the entire 15 m³ ingress has been retained.

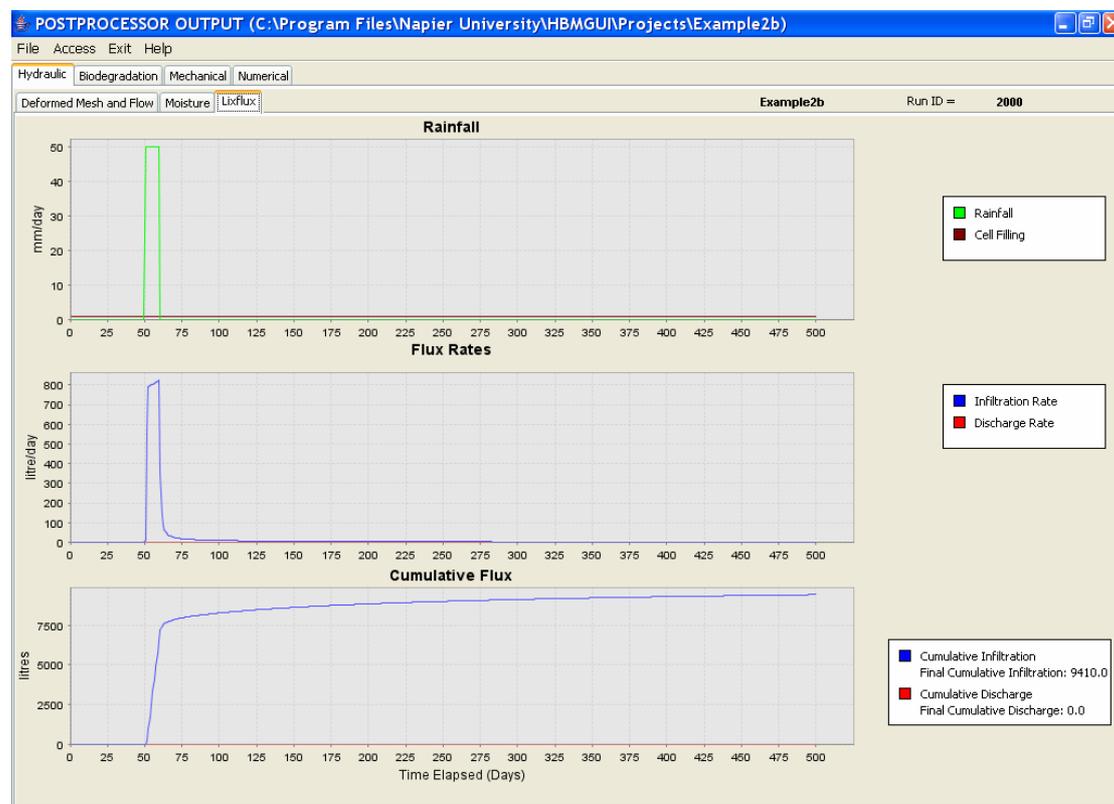
A reported flux discrepancy of this magnitude is not unusual. Accurate boundary flux calculations are difficult to obtain from elements when flow vectors include components that are tangential to the system boundary. Indeed, a sump at the bottom left corner of the landfill section is not a system geometry in which accurate discharge flux measurements can be made. However, a more sophisticated meshing facility than that included with this GUI would be required to refine the geometry at discharge locations. In the absence of such a refinement, a lack of accuracy in **discharge** flux reporting must be accepted.

Although discharge flux monitoring is susceptible to simple mesh geometries, **infiltrative** flux conditions are different. Infiltration is applied uniformly to adjacent nodes defining the current ground surface; it is therefore predominantly vertical and normal to a horizontal upper surface boundary. Despite an exclusively normal boundary flux, problems can arise when moisture contents change sharply across an element. There are, however, a number of controllable factors through which a simulation can be refined in order to obtain the highest level of accuracy; the cost is usually a heavier computational demand. Notwithstanding local mesh refinement, these factors are time step, global element size, and hydraulic conductivity, each of which is considered briefly below.

Time step

Inspection of the hydraulic flux pane for Example 2 shows flux rates firstly oscillating then stabilising but with little sign of converging on the prescribed ingress of 1,500 litres/day; in fact

a cumulative flux of about 8,500 litres is predicted. Oscillatory behaviour of this form can occur if the solution time step is too large, so Example 2 has been re-run with a time step of 0.01 days (as Example 2b). The reduced time step means the simulation will take about 20 times longer (≈ 5 hours) than the original Example 2 (≈ 15 mins). Hydraulic flux panes for Example 2b show that there is less oscillatory behaviour but only a small improvement in predicted flux magnitudes, which are now 9410 litres.



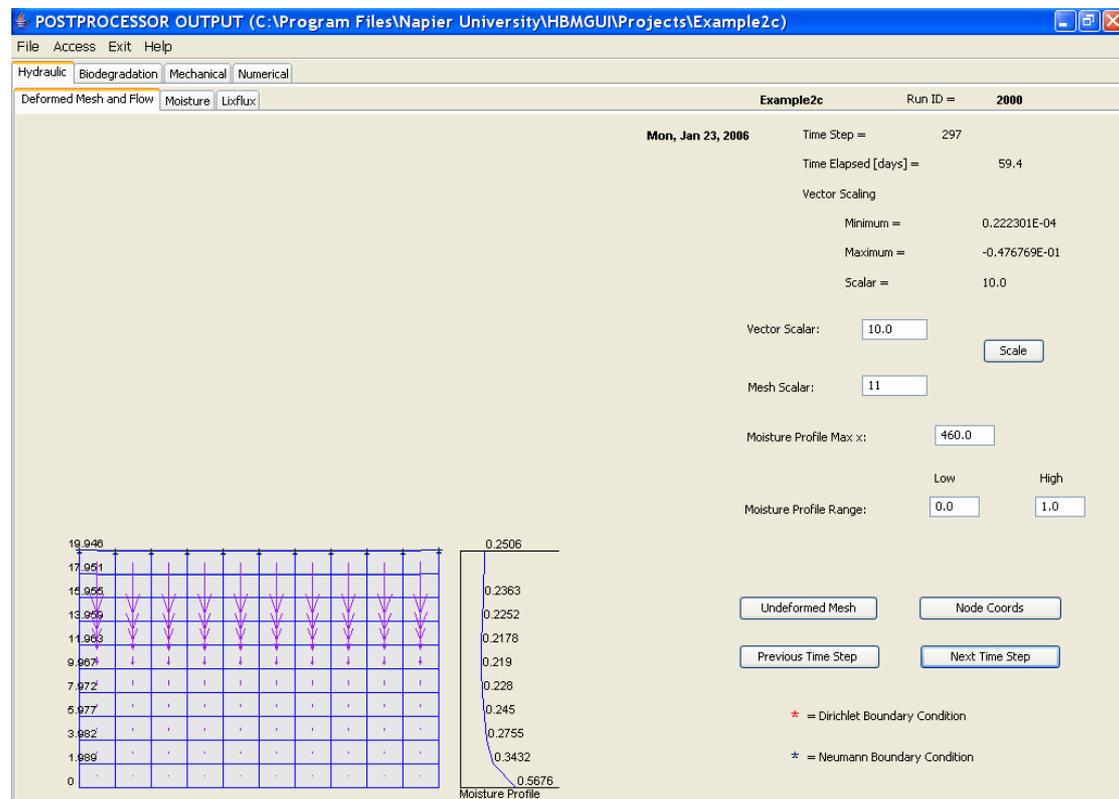
Saturated hydraulic conductivity

A pronounced spatial variation in moisture contents, such as would be present around a distinct wetting front also presents a difficulty for flux reporting. In this case, the unsaturated hydraulic conductivity, which is averaged over each element, tends to under-estimate the infiltrative flux. This is because in large elements, boundary fluxes penetrate only a short distance into the element during any single time step. Internal nodes then retain their pre-

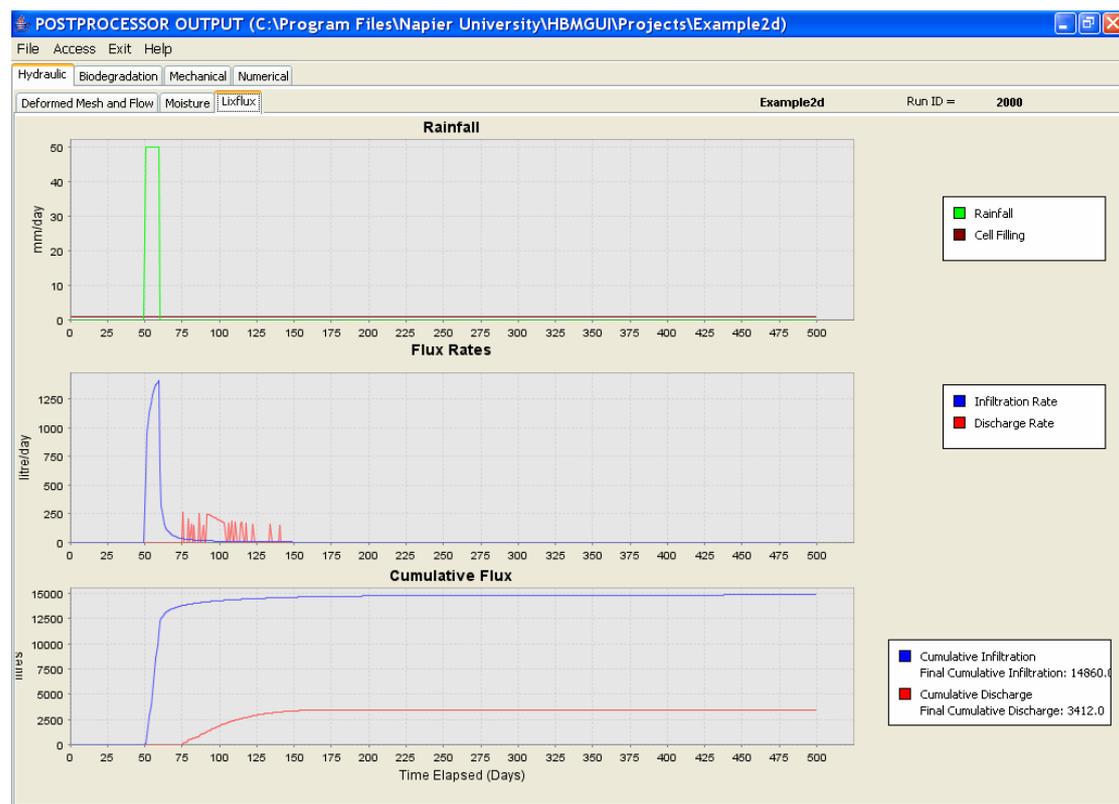
existing lower moisture content and unduly influence the element-wide unsaturated hydraulic conductivity.

We can investigate the impact of these variations and the associated hydraulic conductivity averaging by increasing the saturated hydraulic conductivity in order to ensure that infiltrative flux penetrates beyond the monitored element. The consequence of this is that the elements in question have uniform moisture contents and thereby avoid the problems of conductivity averaging and benefit from a more stable numerical solution. Example 2c presents such a modification – the saturated hydraulic conductivity is increased to 5×10^{-3} m/s. Time step is 0.2 days, the same as Example 2, as are all other material parameters.

There is a large initial infiltration spike, which appears to have a significant and unacceptable impact on cumulative flux. Interestingly, the trend of the infiltrative flux rate is towards a steady value of about 1500 litres/day. Deformed mesh and flow plots for day 59 clearly indicate infiltration has extended beyond the top two layers of elements and also report a maximum vector modulus of 0.476769×10^{-1} [m/day] (in the top right hand corner of the pane).



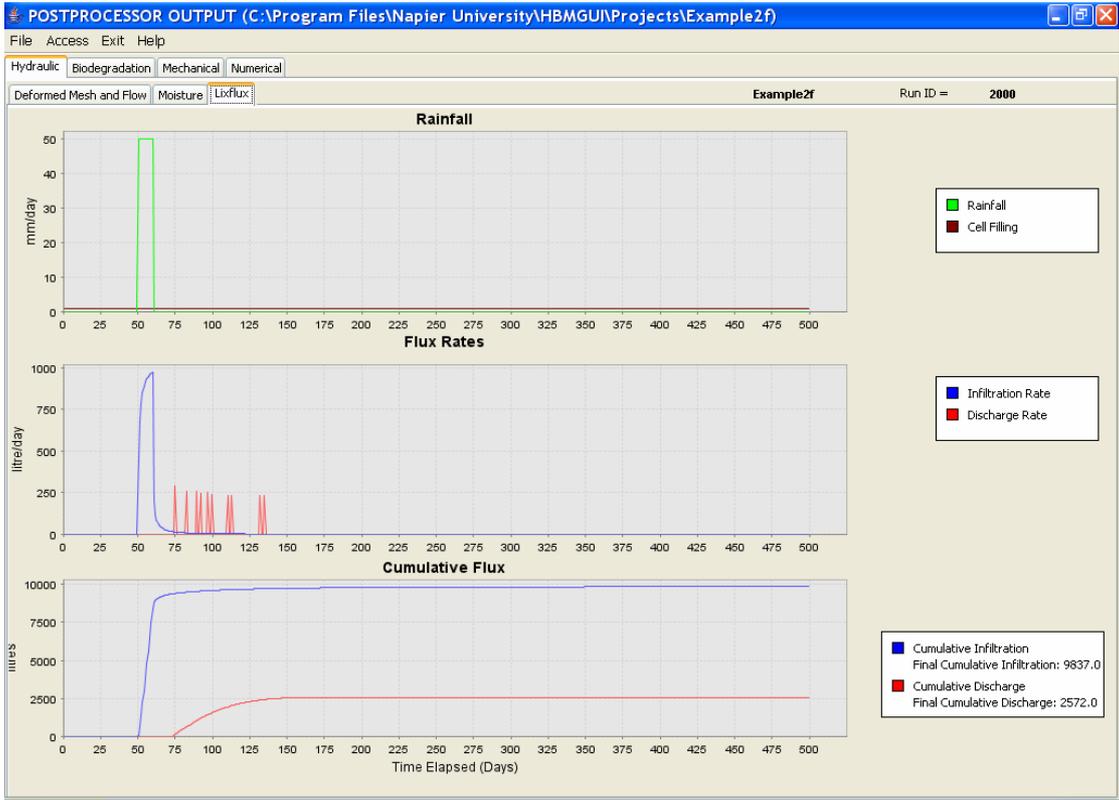
In order to remove the infiltration spike, another simulation (Example 2d) was run with a smaller time step, of 0.1 days. All other parameters remain as in Example 2c. In this case, the spike is lost and the infiltration rate rises steadily towards 1500 litres/day. Cumulative infiltration is reported to be 14,860 litres – an improved performance.



Global element size

Although local mesh refinement is not possible within the HBM GUI mesh generator, a wholesale re-meshing is possible. We have repeated the scenario of Example 2d as Example 2f, with a mesh comprising $15 \times 10 = 150$ elements but over a 20 m wide section profile. Individual element size is thus 2m wide by 1.33 m high, whereas the previous element size was 3m wide by 2m high. The increase in mesh density has a significant computational cost but from the simulation we observe that infiltrative flux rates and cumulative infiltration figures compare well with prescribed event. Note also that the time step is 0.05 days and the saturated hydraulic conductivity is 5×10^{-3} m/s. Infiltration of 50 mm/day

over the 20 m wide section generates a flux rate of 1000 litres/day. Under these more favourable simulation conditions, the predicted infiltration rate rises sharply and smoothly towards the prescribed value and cumulative infiltration over the 10 day event period is reported to be 9837 litres. A much better performance all round although computationally more demanding – about three hours run time.



Phase-dependent saturated hydraulic conductivity

Instead of providing a single global saturated hydraulic conductivity, the value for each element can be calculated within the HBM model according to the contemporaneous phase composition. This is set by setting the saturated hydraulic conductivity in the materials pane to -1 .

Through this device, load-induced, and to a certain extent decomposition-induced changes, in conductivity can be accommodated. The calculation is based on data published by Beaven (2000) that relate saturated hydraulic conductivity to load/density; further details are given in the Theory Manual.

The HBM model calculates the saturated hydraulic conductivity from a void to inert ratio rather than density data. In this way an increase in aggregated solid density arising from the loss of the (lower particle weight) degradable fraction, rather than compression, does not reduce the hydraulic conductivity when an increasingly open structure is working to bring about a higher conductivity. It should be noted that the formulation is a first approximation; it is based on data from fresh waste and so does not explicitly account for any changes in texture or fabric of the waste skeleton nor changes in viscosity of leachate that may occur with degradation. It does, however, begin to accommodate the wide range of bulk saturated hydraulic conductivities measured under load in large scale experimental facilities

In addition to the internally controlled saturated hydraulic conductivity, the simulation has a time step of 0.05 days to control oscillations. In all other respects the simulation is identical to Example 2.

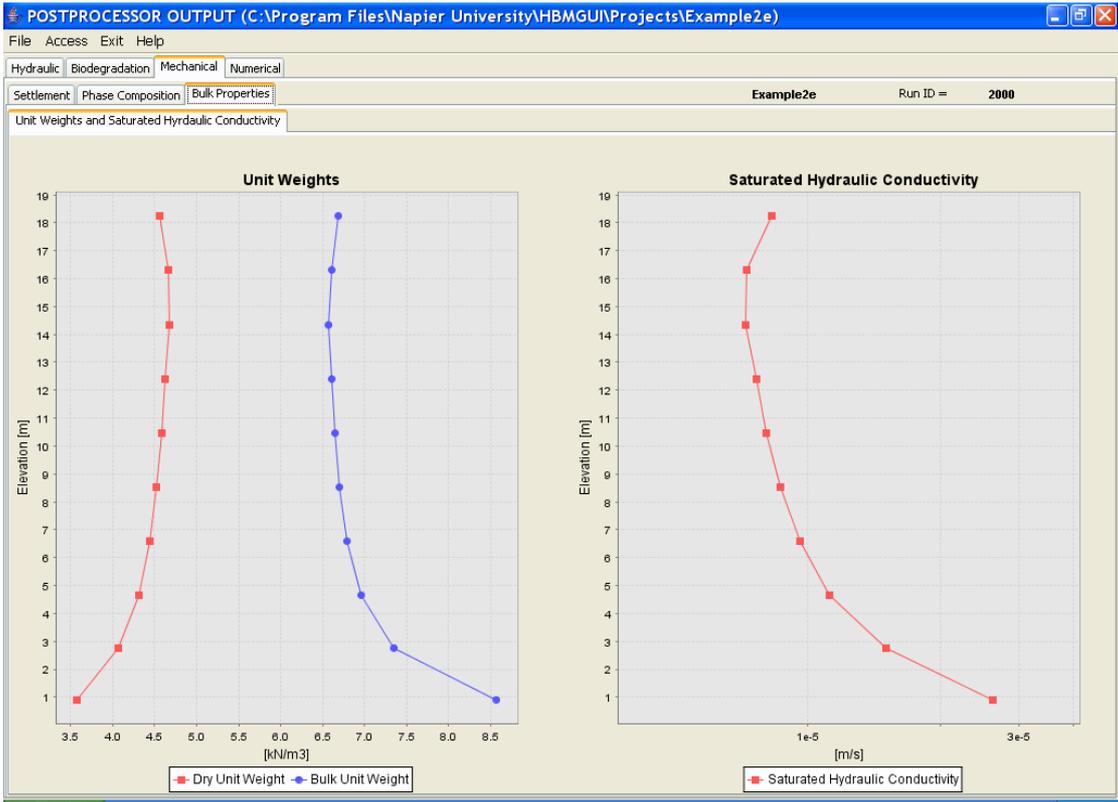
Go to the Material Properties pane,

✦ Set *Saturated Hydraulic Conductivity* = -1

Write the input files and run the simulation.

From the saturated hydraulic conductivity profile, we see that the lowest saturated conductivity of about 0.7×10^{-5} m/s occurs between 14-16 m elevation. In the top element,

saturated conductivity is a little greater, whereas at the base it is higher still, at about 2.6×10^{-5} m/s. The range of conductivities, which are echoed by the dry unit weight profiles, are consistent with the presence of greater amounts of moisture and hence decomposition.



Example 2: Summary of simulation modifications

Example	Time step [days]	K_{sat} [m/s]	Outcomes
2	0.2	5×10^{-5}	Base simulation: Oscillations in flux rate Rate = c800 litres/day Cumulative = 8256 litres
2b	0.01	5×10^{-5}	No oscillations Rate = c800 litres/day Cumulative = 9410 litres
2c	0.2	5×10^{-3}	Infiltration rate spike Rate approaches 1,500 litres/day Cumulative = excessive
2d	0.1	5×10^{-3}	No infiltration rate spike Rate approaches 1,500 litres/day Cumulative = 14,780 litres
2e	0.05	Internal	See next section
2f	0.05	5×10^{-3}	Smaller element – 2m x 1.33m Rate approaches 1000 litres/day Cumulative = 9837 litres

Example 3: Two Dimensional Homogeneous Landfill Section with Inoculum Addition

Project directory – Example3

This example is identical to Example 2c, that is with a saturated hydraulic conductivity of 5.0×10^{-3} m/s and time step of 0.2 days, but with the addition of inoculum rather than raw water. The inoculum is handled through influent VFA and MB concentrations.

To Start the New Example

- ✦ Start the GUI using the desktop icon.

From the Open Project file chooser, a number of options exist. This example can be:

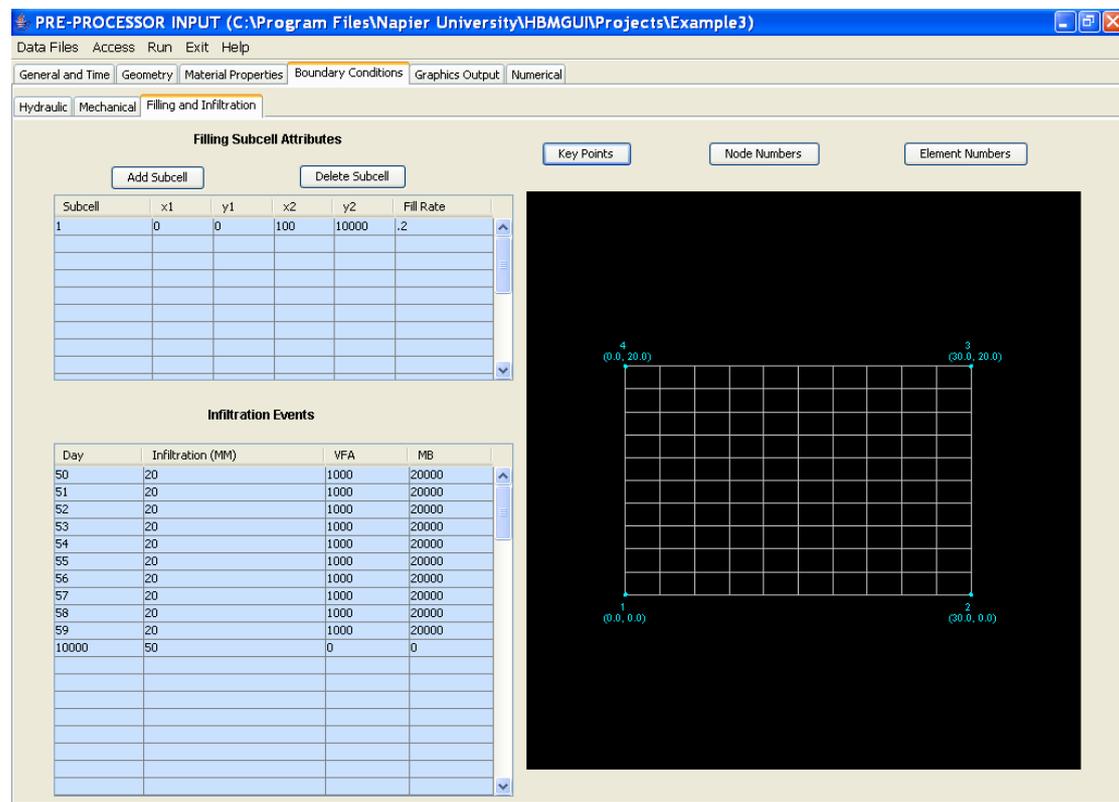
- Built from scratch following the input instructions of Example 1 & 2 and the additional model building described below. Open a new project directory
- As an extension to Example 2, whereby only the additional model building described below is undertaken. Open *Example2* (or your previously defined project name).
- By following the existing project directory. Open *Example3*.

MODEL BUILDING - PREPROCESSOR

Biodegradation – Boundary conditions

In the Boundary Conditions pane, Infiltration sub-pane, set VFA and MB concentrations for each of the infiltration days to 1,000 and 20,000 [g/m³] respectively.

Other hydraulic, infiltration, biodegradation and mechanical boundary conditions are unchanged so it remains only to write data files and run the program.

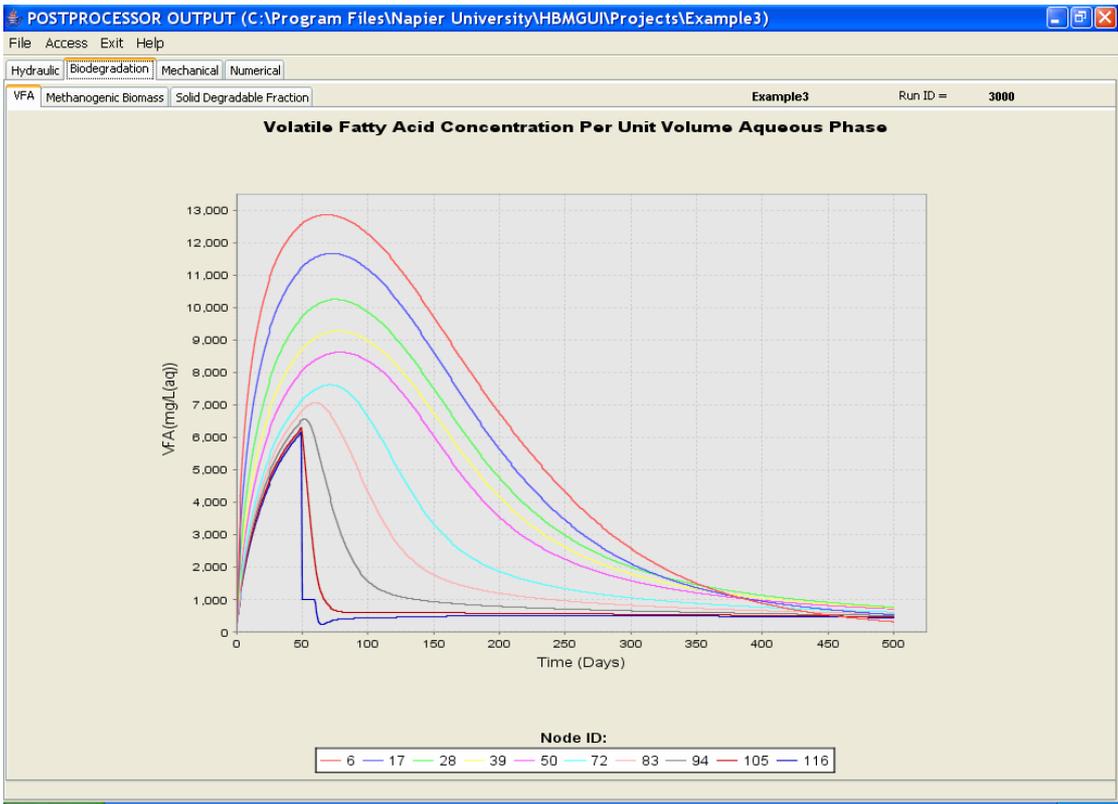


OUTPUT DATA - POSTPROCESSOR

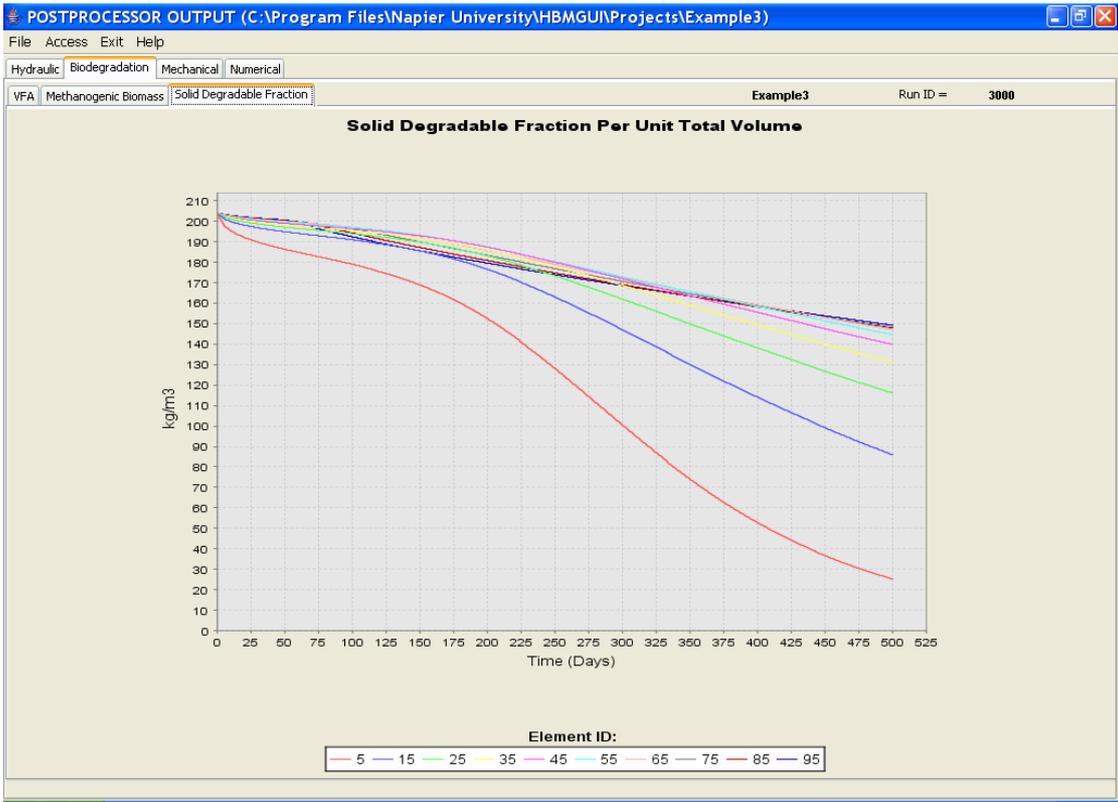
The output data shown below compare directly with those obtained from Example 2c.

Biodegradation

In addition to the flushing effect, the addition of inoculum markedly increases MB concentrations. A direct consequence is the very rapid consumption of VFA in the upper part of the section.



High MB concentration and consumption of VFA will also stimulate solids depletion. This is certainly the case for Element 95 at the infiltration surface, and underlying elements. Degradable fractions in Element 95 at the end of this simulation are about 150 kg/m³ whereas at the end of Example 2c, Element 95 had a degradable fraction of about 170 kg/m³.



Example 4: Two Dimensional Landfill Section with Drainage Layer & Raw Water Addition

Project directory is Example4

This example illustrates the use of more than one material property set. An inert drainage layer is introduced along the base and sides of the landfill section and distinguished by changes to a number of material properties, notably the saturated hydraulic conductivity. In order to accommodate the hydraulic conductivity contrast between the drainage layer and the waste, a time step of 0.05 days has been used.

To Start the New Example

- ✦ Start the GUI using the desktop icon.

From the Open Project file chooser, a number of options exist. This example can be:

- Built from scratch following the input instructions of Examples 1 & 2 and the additional model building described below. Open a new project directory
- As an extension Example 2, whereby only the additional model building described below is undertaken. Open *Example2* (or your previously defined project name).
- By following the previously built model. Open *Example4*.

MODEL BUILDING - PREPROCESSOR

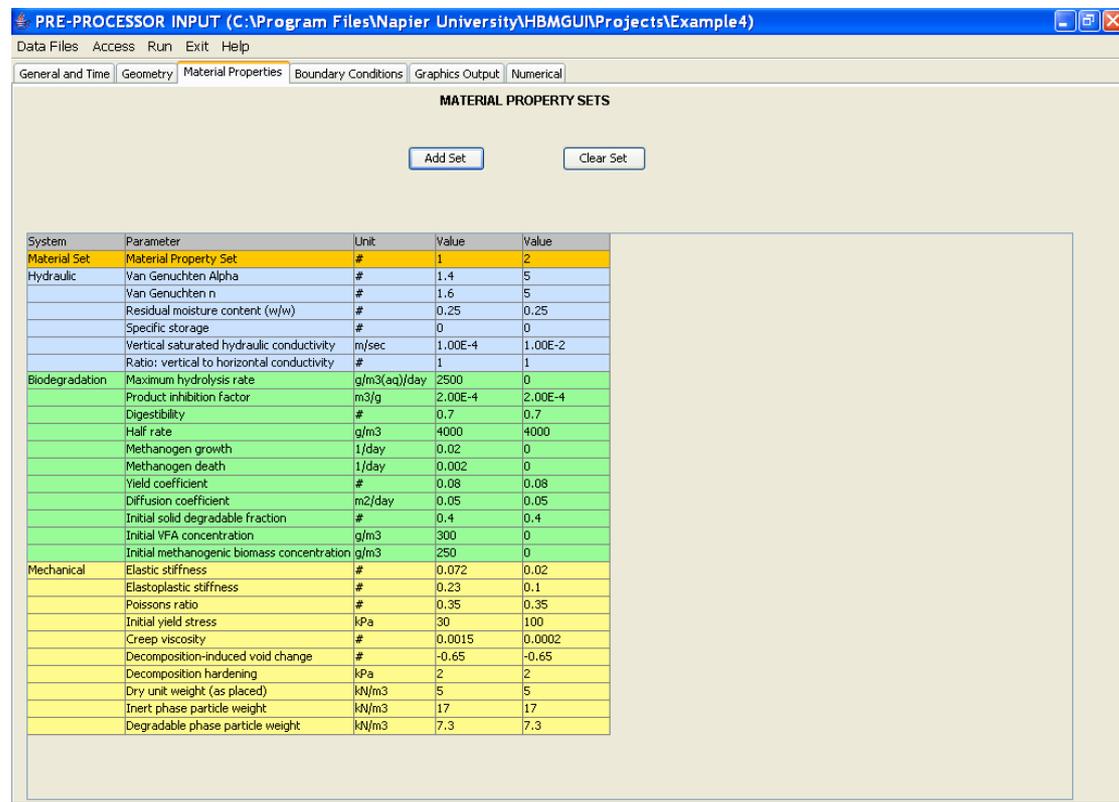
Material Properties

In the Material Properties pane,

- ✦ Click on *Add Set*.
- ✦ Select the *Inert* radio button
- ✦ Click on *OK*

A new material property set appears with the *set number* = 2, shown in the topmost (gold shaded) row.

Biodegradation is de-activated and the stiffness increased for an inert drainage layer. A table summarising the biodegradation and other material property settings can be found in Appendix 1.



PRE-PROCESSOR INPUT (C:\Program Files\Napier University\HBMGUI\Projects\Example4)

Data Files Access Run Exit Help

General and Time Geometry Material Properties Boundary Conditions Graphics Output Numerical

MATERIAL PROPERTY SETS

Add Set Clear Set

System	Parameter	Unit	Value	Value
Material Set	Material Property Set	#	1	2
Hydraulic	Van Genuchten Alpha	#	1.4	5
	Van Genuchten n	#	1.6	5
	Residual moisture content (w/w)	#	0.25	0.25
	Specific storage	#	0	0
	Vertical saturated hydraulic conductivity	m/sec	1.00E-4	1.00E-2
	Ratio: vertical to horizontal conductivity	#	1	1
Biodegradation	Maximum hydrolysis rate	g/m3(aq)/day	2500	0
	Product inhibition factor	m3/g	2.00E-4	2.00E-4
	Digestibility	#	0.7	0.7
	Half rate	g/m3	4000	4000
	Methanogen growth	1/day	0.02	0
	Methanogen death	1/day	0.002	0
	Yield coefficient	#	0.08	0.08
	Diffusion coefficient	m2/day	0.05	0.05
	Initial solid degradable fraction	#	0.4	0.4
	Initial VFA concentration	g/m3	300	0
	Initial methanogenic biomass concentration	g/m3	250	0
Mechanical	Elastic stiffness	#	0.072	0.02
	Elastoplastic stiffness	#	0.23	0.1
	Poissons ratio	#	0.35	0.35
	Initial yield stress	kPa	30	100
	Creep viscosity	#	0.0015	0.0002
	Decomposition-induced void change	#	-0.65	-0.65
	Decomposition hardening	kPa	2	2
	Dry unit weight (as placed)	kN/m3	5	5
	Inert phase particle weight	kN/m3	17	17
	Degradable phase particle weight	kN/m3	7.3	7.3

It is now necessary to assign the inert material property set number to the corresponding model elements.

- ✦ Return to the Geometry pane

Geometry

On the Geometry pane, change the mesh view to element numbers,

- ✦ Click on *Element Numbers*.
- ✦ In the *Element Assignment Table*: assign *Material Property Set number = 2* to elements
 - 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 (the base)
 - 11, 21, 31, 41, 51, 61, 71, 81 (left side - except top-most element)
 - 10, 20, 30, 40, 50, 60, 70, 80, 90 (right - except top-most element)

Remember, a copy and paste facility is available by right clicking on the mouse.

Since the hydraulic and infiltration boundary conditions are unchanged, it remains only to write data files and run the program.

OUTPUT - POSTPROCESSOR

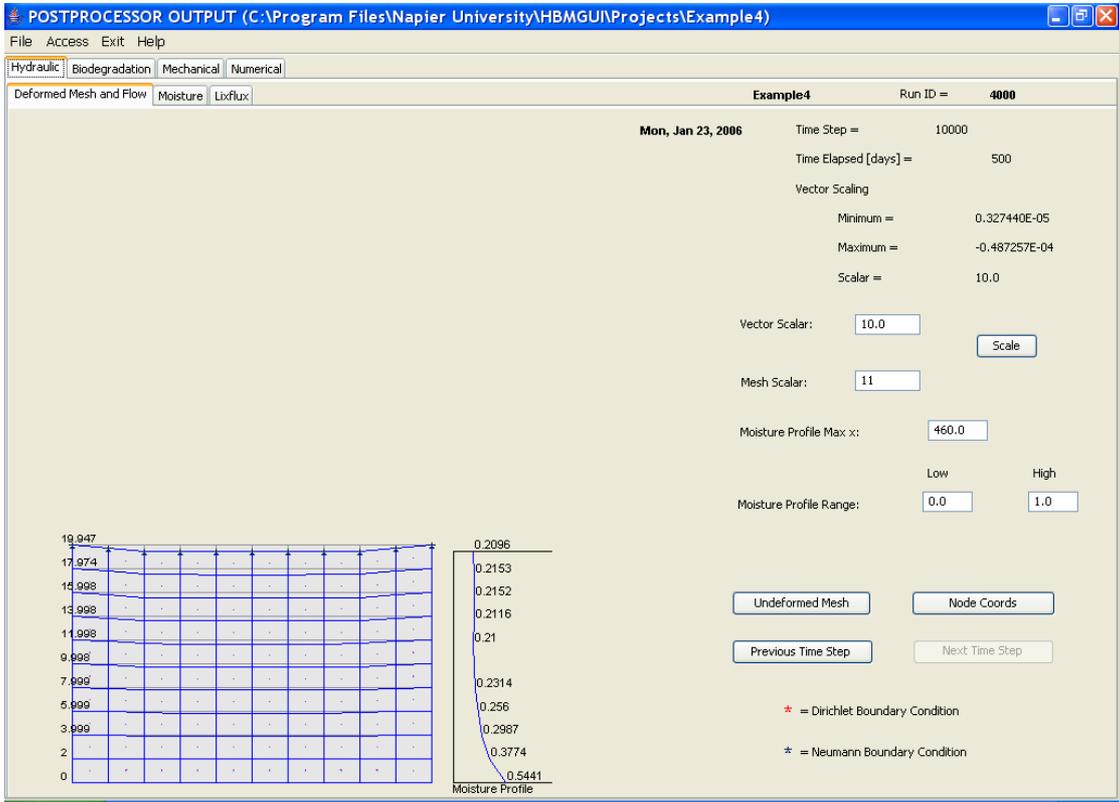
The output data shown below compare directly with those obtained from Example 2. The main differences are that the drainage layer is inert, retains less moisture, is stiffer and two orders of magnitude more permeable. There is no VFA or MB initially present in the drainage layer.

Hydraulic

Deformed Mesh & Flow

It is evident from the end of run figure that:

- the drainage layer has a different porosity and hence moisture content,
- the stiffer drainage layer has undergone negligible compression.



Lixflux - mass balance

Infiltrative flux fails to reach the prescribed boundary flux although the upper elements are clearly retaining more moisture at the end of the simulation than they were at the start.

Biodegradation

Organic fraction depletion in Element 5, in the drainage layer, shows an unchanged degradable content. All other elements depicted show degradable fractions falling from 204 kg/m³ to values in the range 100 - 160 kg/m³.

Example 5: Waste Column with Filling & Fixed Initial Moisture Content: Moisture Effects, Biodegradation & Settlement

Project directory is Example5

This example introduces waste filling. Moisture redistribution, biodegradation and settlement are followed during filling and for about 650 days thereafter. The problem scenario is idealised as a waste column, 20m high when unloaded, with initial volumetric moisture content of 0.3. Filling is depicted by a process of element placement over a period of about 850 days; total simulation period is 1500 days.

To Start the New Example

- ✦ Start the GUI using the desktop icon.

From the Open Project file chooser, a number of options exist. This example can be:

- Built from scratch following the model building described below. Open a new project directory
- By following the previously built model. Open *Example5*.

MODEL BUILDING - PREPROCESSOR

General data and time control

- ✦ Enter *Job number & name*.
- ✦ Enter *Job name*.

Assignment of the initial (or as-placed) moisture content of the imported waste to each element, together with corresponding hydraulic pressure values, is done by the *Initialise Moisture* option, which instigates a steady state hydraulic analysis.

- ✦ Select *Initialise Moisture* in the *Analysis Type* option box.

The following two data inputs are only relevant to transient or time-dependent analyses. They are, however, data that are read during run-time, hence it is necessary to provide input values.

- ✦ Enter *Time Step Increment* [days] = 0.2
- ✦ Enter *Duration* [days] = 1500

Geometry

- ✦ Click on the *Geometry* pane tab.

If using pre-existing model data, the mesh geometry will be visible in the graphics pane on the right.

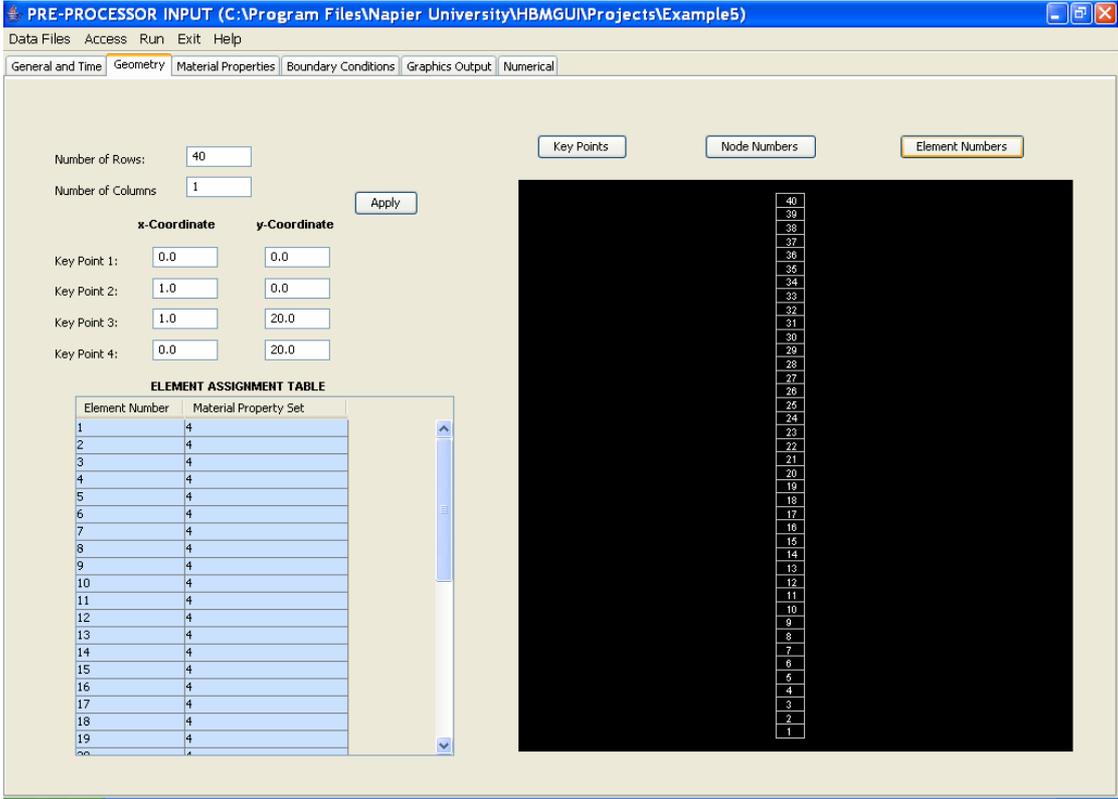
Building 'from scratch', enter the following data.

- ✦ *Number of Rows* = 40
- ✦ *Number of Columns* = 1
- ✦ *Keypoint data* - x & y coordinates (in metres):

Keypoint	x	Y
1	0.0	0.0
2	1.0	0.0
3	1.0	20.0
4	0.0	20.0

✦ Click *Apply*, to update and see the configured mesh.

Clicking on switches above the viewing pane annotates the mesh in the viewing pane with keypoint, node or element numbers.



Material Properties

- ✦ Click on *Material Properties* pane tab.

Building 'from scratch', add a material property set.

- ✦ Click on *Add Set*: A dialog box appears.
- ✦ Select the *Biodegradable* option, then click on *OK*.

A set of (biodegradable) waste material properties appears. Under *Basic* access (default), only *Material Property Set* number the *Initial Solid Degradable Fraction* and *Bulk Unit Weight (as placed)* are defined. All other material properties are inaccessible (greyed out) until the advanced option is selected.

Infilling - disclosable elements

The *Material Property Set number* defaults to the lowest available number but values of 4 or greater define elements that are controlled to simulate the filling process. In fact, five material property set numbers, 4 to 8 inclusive, are currently dedicated to fill elements.

When filling, all 'fill elements' are initially de-activated, in effect hidden or excluded from the hydro-bio-mechanical analysis. This is achieved by temporarily assigning to them the *Material Property Set* number = 9. Hydraulic effects are excluded by a very low saturated hydraulic conductivity, diffusive transport is constrained by a low diffusion coefficient, biodegradation is stopped by assigning zero values to the maximum hydrolysis rate, methanogen growth rate, and methanogen death rate.

Hidden elements are subsequently disclosed according to some known filling pattern. On disclosure, the original material property set number and associated parameters are restored; disclosed elements then partake in the HBM analysis as moisture redistribution, species transport and biodegradation begin. Element stiffness' are not changed during de-activation but on disclosure, body forces are applied so self-weight compression of underlying fill is triggered. Creep effects do not occur whilst an element is de-activated.

To configure the simulation for infilling:

- ✦ Set *Material Property Set Number* = 4
- ✦ Click on *Add Set*: A dialog box appears.
- ✦ Select the *Biodegradable* option, then click on *OK*.
- ✦ Set *Material Property Set Number* = 9
- ✦ Modify selected material property set values for set 9 as given by the table in Appendix 1.

Note that it is necessary to change access level from basic to advanced to make these changes.

System	Parameter	Unit	Value	Value
Material Set	Material Property Set	#	4	9
Hydraulic	Van Genuchten Alpha	#	1.4	1.4
	Van Genuchten n	#	1.6	1.6
	Residual moisture content (w/w)	#	0.25	0.25
	Specific storage	#	0	0
	Vertical saturated hydraulic conductivity	m/sec	5.00E-5	1.00E-15
	Ratio: vertical to horizontal conductivity	#	1	1
Biodegradation	Maximum hydrolysis rate	g/m ³ (aq)/day	2500	0
	Product inhibition factor	m ³ /g	2.00E-4	2.00E-4
	Digestibility	#	0.7	0.7
	Half rate	g/m ³	4000	4000
	Methanogen growth	1/day	0.02	0
	Methanogen death	1/day	0.002	0
	Yield coefficient	#	0.08	0.08
	Diffusion coefficient	m ² /day	0.05	0.005
	Initial solid degradable fraction	#	0.4	0.4
	Initial VFA concentration	g/m ³	300	300
	Initial methanogenic biomass concentration	g/m ³	250	250
Mechanical	Elastic stiffness	#	0.072	0.072
	Elastoplastic stiffness	#	0.23	0.23
	Poissons ratio	#	0.35	0.35
	Initial yield stress	kPa	30	30
	Creep viscosity	#	0.0015	0.0015
	Decomposition-induced void change	#	-0.65	-0.65
	Decomposition hardening	kPa	2	2
	Dry unit weight (as placed)	kN/m ³	5	5
	Inert phase particle weight	kN/m ³	17	17
Degradable phase particle weight	kN/m ³	7.3	7.3	

- ✦ Return to the *Geometry* pane to check that all elements in the *Element Assignment Table* are assigned the element material property set number, i.e. 4, in right hand column.

Boundary Conditions

Assignment of the initial (or as-placed) moisture content of the imported waste to each element, together with corresponding hydraulic pressure values, is done by the *Initialise Moisture* option. This setting instigates a steady state hydraulic analysis

In this example, an initial as-placed moisture content of 0.3 by volume is assumed. For the waste in question, with a dry density of 5 kN/m³, 300 litres (or 2.943 kN) of moisture per m³ of total volume corresponds to 37% moisture content by wet weight and 59% by dry weight.

Hydraulic

It is necessary to define a number of nodes, distributed over the problem domain, to guide the numerical solution. In order to create a constant initial moisture content it is necessary to assign a negative pressure head value to each of the specified nodes. For the soil water retention properties in question, a pressure head of –3.0m will generate a volumetric moisture content of 0.2996. We have chosen to prescribe this pressure head to 10 nodes scattered throughout the column.

- ✦ From the *Boundary Conditions* pane, select the *Hydraulic* sub-pane
- ✦ Click on *Node Numbers* to show necessary node number information
- ✦ Set *Hydraulic Sets* spinner box = 1.

For base hydraulic boundary conditions, in the first data group:

- ✦ Set *Type* spinner box to *Perm Dirichlet*
- ✦ Enter *Number Of Nodes* = 10
- ✦ Enter *Prescribed Value* = –3.0m
- ✦ Enter *Node Numbers* = 1, 2, 21, 22, 41, 42, 61, 62, 81, 82 (No commas; each number separated by a space).

Mechanical

It is necessary to provide some fixity or zero displacement conditions for the landfill section. In this case, the base nodes (1 & 2) are fixed in both x & y directions (code = 2), the sides nodes (all others) are fixed in the x-direction only (code = 1).

- ✦ Enter code 1 into all cells of the *Nodal Fixities Table*, except nodes 1 & 2, for which the code 2 should be entered.

Remember, cut and paste options are available using the right-mouse button.

Infilling & Infiltration

Here, filling progresses uninterrupted up the full column height. In the filling table, enter a nominal set of coordinates that comfortably embraces and exceeds the vertical height of the waste column. A filling rate of 0.02 m/day results in a 20m column of unloaded waste being filled in about 800-900 days.

- ✦ Enter in cells of the first row of the *Filling Subcell Table*,
- ✦ *Subcell* = 1; *x1* = 0.0; *y1* = 0.0; *x2* = 100.0; *y2* = 10000.0; *Fill Rate* = 0.02

Ensure dummy variables are present to avoid end of file errors in the Infiltration table.

- ✦ Enter in the cells of the first row of the *Infiltration Table*,
- ✦ *Day* = 10,000; *Infiltration* = 50; *VFA* = 0; *MB* = 0.

The Infilling and Infiltration sub-pane should now look like the figure below.

Graphics Output Control

Degradable content and other element properties are monitored in (up to) ten elements distributed evenly down the length of the column.

- ✦ Enter *Number Of Elements* = 10
- ✦ Enter *Elements* = 1, 3, 5, 10, 15, 20, 25, 30, 35, 40 (No commas)

Infiltration/discharge are monitored at the column base.

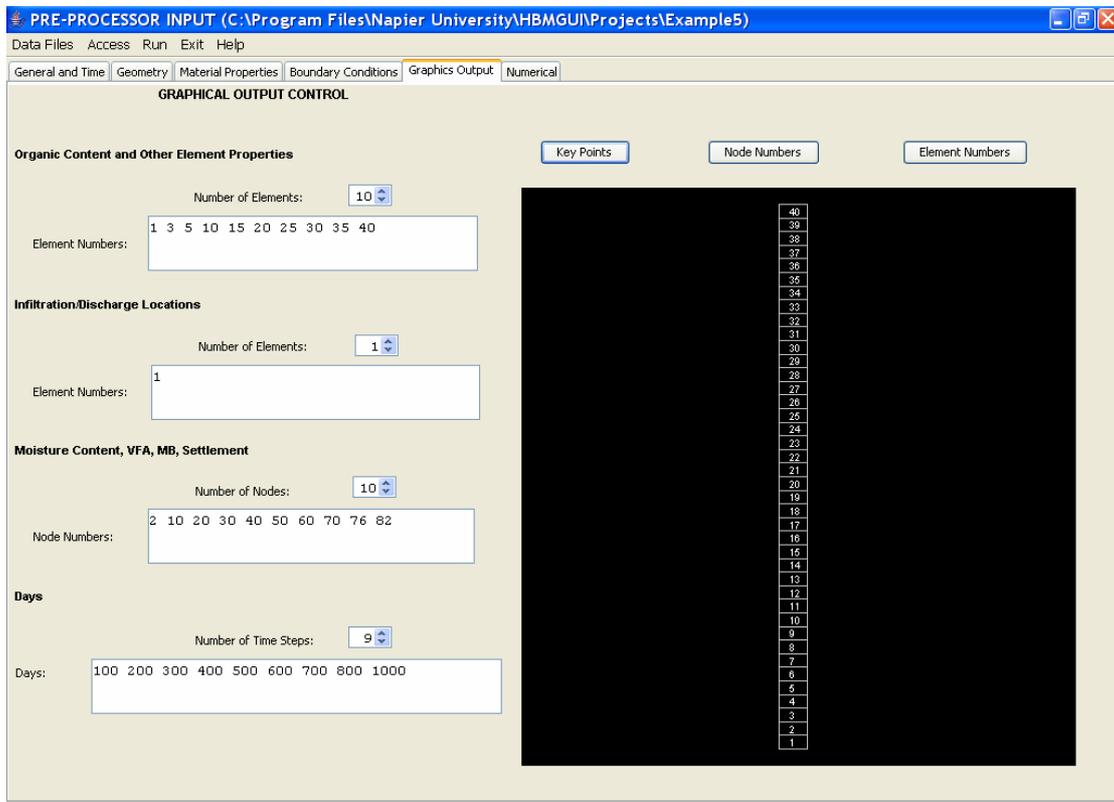
- ✦ Enter *Number of Elements* = 1
- ✦ Enter *Elements* = 1

Moisture content, VFA, methanogenic biomass and settlement are monitored at (up to) ten nodes attached to the ten elements monitored for degradable content.

- ✦ Enter *Number of Nodes* = 10
- ✦ Enter *Nodes* = 2, 10, 20, 30, 40, 50, 60, 70, 76, 82 (No commas)

Element and nodal data items referred to above are monitored on (up to twelve) predetermined days. In this case 9 days are to be monitored:

- ✦ Enter *Number of Days* = 9
- ✦ Enter *Data days* = 100, 200, 300, 400, 500, 600, 700, 800, 1000 (No commas)



Saving the model and writing data files

The model is now ready to run. It is necessary to save the GUI data and create HBM input data files before running the model.

- ✦ From *Data Files* drop down menu, click on *Write Data*.

Note that there is no validation of input data. However, missing files and/or incorrectly formatted data should be captured by normal Fortran or Java run time error messages.

The prepared model must be saved and HBM input data files created by clicking on WRITE DATA before each solution.

SOLUTION

The initialise moisture analysis, set on the Time and General pane, establishes an initial hydraulic condition, i.e. a moisture distribution profile and consistent pressure heads. This information is necessary to control the initial conditions of a time-dependent simulation.

- ✦ From *Run* drop down menu, click on *Run Engine*

A dialog box appears.

- ✦ Click *OK* to confirm the run engine command.

A DOS window will be seen momentarily, after which it is possible to proceed to the postprocessor. If hydraulic boundary conditions have been correctly specified, the HBM engine will find a solution to the initial moisture analysis very quickly.

INITIAL OUTPUT - POSTPROCESSOR

To access the post processor,

- ✦ From drop-down *Run* menu, click on *Run Postprocessor*

The postprocessor starts at the *Deformed Mesh & Flow* sub-pane of the *Hydraulics* pane.

Deformed Mesh & Flow

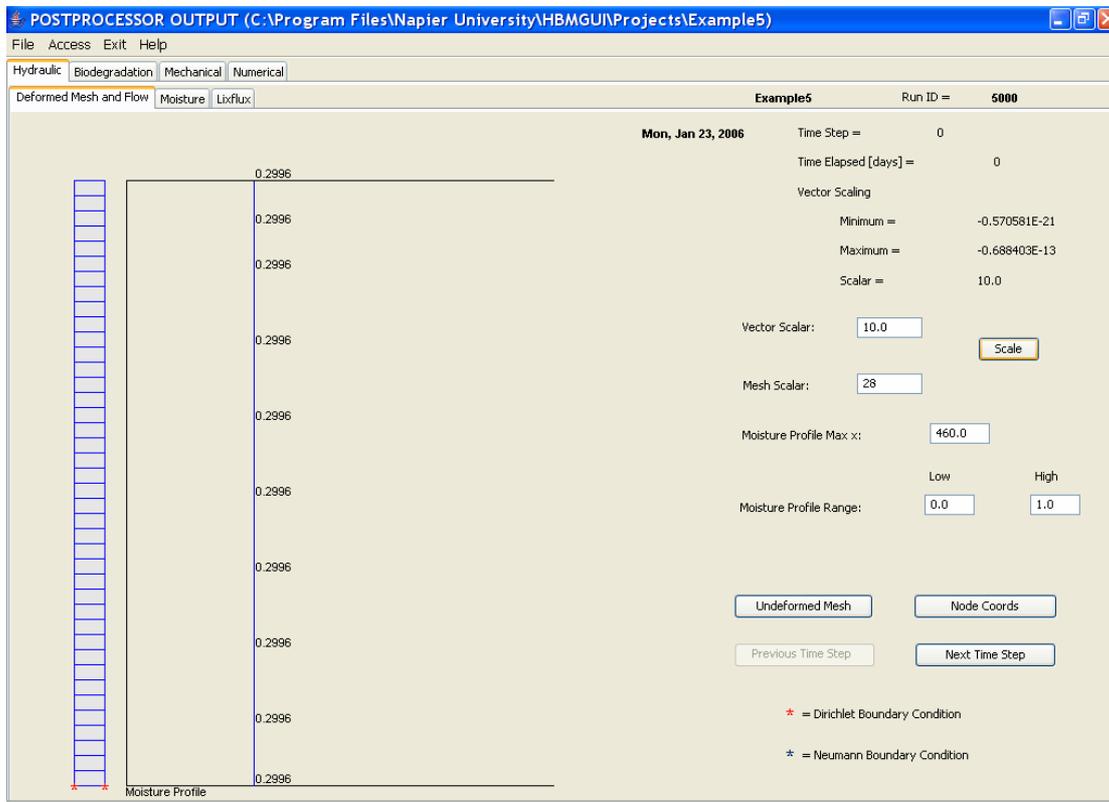
To rescale the view,

- ✦ Enter *Scale Factor* = 28, then
- ✦ Click the *Scale* button.

Advance the view from the numerical 'pre-solution' to the initial moisture contents.

- ✦ Click on *Next Time Step*

The moisture profile, which should show 0.2996 over the full length of the column, corresponds to the nodes defined in the graphics output control.



Bulk Properties

To view the initial (as-placed) bulk and dry unit weights and saturated hydraulic conductivity.

- ✦ Click on *Mechanical - Bulk Properties - Unit Weights & Saturated Hydraulic Conductivities*.

To return to the pre-processor and run the time dependent analysis:

- ✦ From drop-down *Exit* menu, click on *Exit*.

Return to the pre-processor will be at the point of departure.

MODELLING TRANSIENT BEHAVIOUR - PREPROCESSOR

To investigate self-weight filling, creep and biodegradation settlement behaviour over time, we have to ensure that the hydraulic boundary conditions in the column are consistent with any settlement. This is achieved by removing all hydraulic boundary conditions except the base conditions, i.e. nodes 1 and 2, which are modified to depict a leachate sump.

Boundary conditions

Hydraulic

The sump condition is automatically activated when pressure heads at the nodes in question become non-negative; in fact a very small negative pressure head is set as the trigger value. Any leachate head accumulating at the sump nodes is then drained. If pressure heads at the sump nodes become negative again then the sump condition is de-activated. Through this control, anomalous infiltration of moisture up into the waste from the sump is avoided.

General & Time

- ✦ From the *General & Time* pane, set the *Analysis Type* to *Transient*

The prepared model must be saved and HBM input data files created by clicking on WRITE DATA

SOLUTION

A DOS window appears and shows some run time information. The runtime information continues to scroll as the solution advances. A runtime error will result in an error message to the screen or the runtime information hanging.

OUTPUT - POSTPROCESSOR

- ✦ From the drop-down *Run* menu, click on *Run Postprocessor*.

Hydraulic

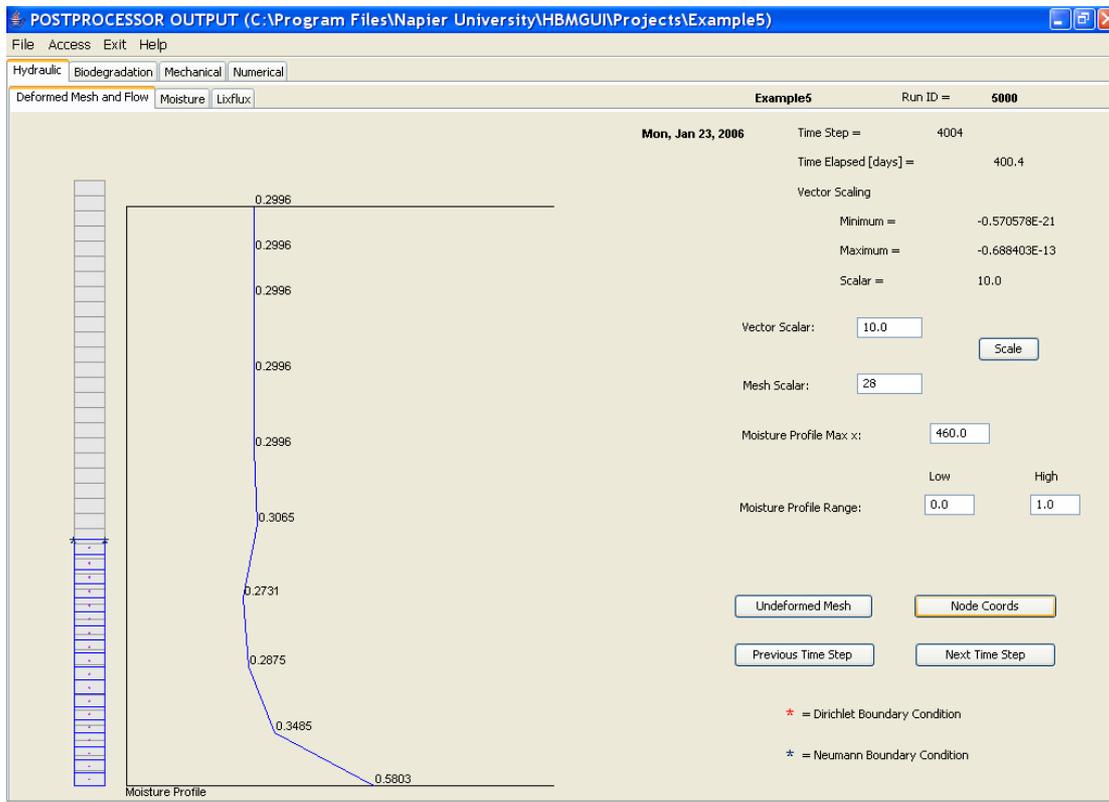
Deformed mesh & flow

The deformed mesh and flow vector sub-pane open up with the hydraulic boundary conditions at the start of the analysis, i.e. time step = 0. This view provides a visual check on the initial hydraulic regime and boundary conditions. No flow vectors are shown in this view.

The deformed mesh, flow vectors and moisture profile plots need to be resized using the on-screen view and range scaling factors.

- ✦ Enter *Mesh Scalar* = 28.
- ✦ Click on *Scale*

The figure below, obtained by clicking repeatedly on *Next Time Step*, show the waste column during filling (day 400). Remember that during filling, the moisture contents shown in the moisture profile diagram at elevations higher than the visible mesh correspond to hidden elements. On disclosure, the initial volumetric moisture content of 0.2996 is redistributed according to the local contemporaneous hydraulic regime. The combined effect of initial moisture content and local conditions on redistribution is well illustrated in the moisture plots.



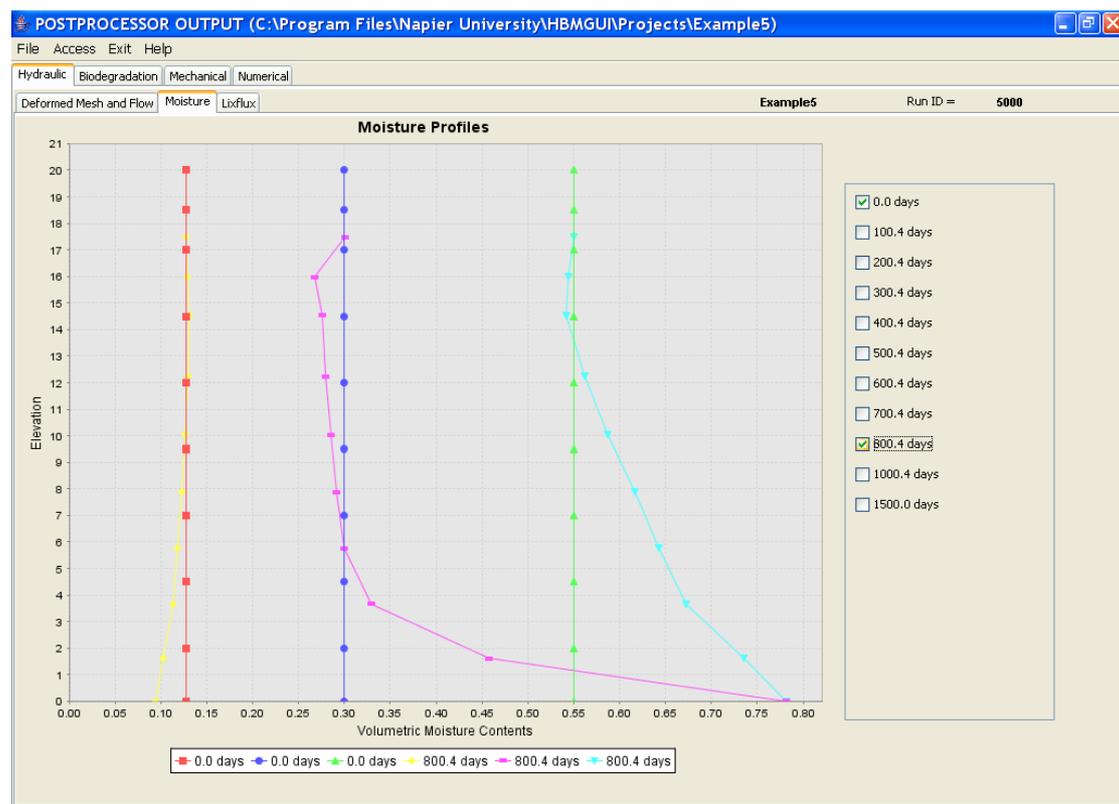
Moisture

Moisture content profiles, residual (left), actual (middle) and saturated (right), can be viewed for any combination of times during the simulation by selecting the appropriate boxes on the right of the pane. The view shown here is for days 0 and 800.

Observe that the actual moisture profile for day 800 is noticeably less than the initial condition from just below the column surface down to about 5m above the base. Beneath this elevation, moisture contents increase sharply to the saturated moisture content/porosity at the column base⁶.

⁶ This is an illustration that moisture retention and by implication the 'absorptive capacity' should not be treated as a cell-averaged constant but is fundamentally related to the hydraulic regime.

Note also the combined impact of self-weight and decomposition-induced phase changes. The saturated moisture content at day 800 is reduced slightly by loading in its upper part. At lower elevations, the greater time that has elapsed since disclosure together with the higher moisture content produce a significant amount of void enlargement.



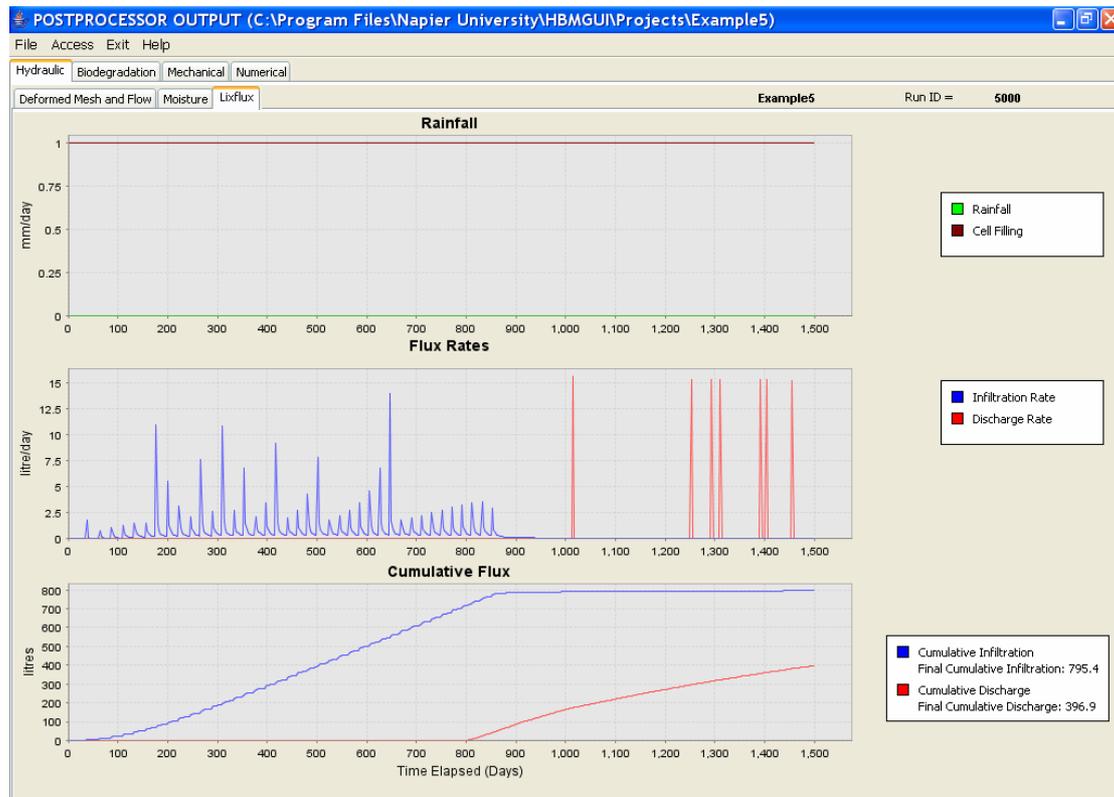
Lixflux

It is necessary to interpret reported fluxes with care when infilling is activated. This is because element flux monitoring cannot distinguish between boundary flows and internal redistribution. It is possible to devise controls for sump or discharge boundary conditions but in their present form they are unable to ensure all non-boundary fluxes are ignored.

In this simulation, no infiltration has been prescribed, so reported infiltrative fluxes correspond to the internal redistribution of moisture from the current topmost (monitored) element towards lower elements. Drainage appears to occur from the column base shortly about day 800,

although corresponding discharge rates, which are reported only during the post-filling period, are inconsistent with the cumulative flux. Clearly cumulative discharge flux reporting has been activated but with no corresponding reported discharge. In fact a discharge event, other than those shown, may have triggered reporting but what is being reported is movement of moisture into the base element. Assuming no significant boundary flows have occurred, i.e. disregarding the reported discharge, a check on the column reveals a hydraulic mass balance that is not indicative of significant liquid discharge (see table below).

[m ³]	Initial condition	End of simulation
Moisture retained	5.99	5.54
Moisture consumed by cellulolytic hydrolysis	-	0.38
Total	5.99	5.92

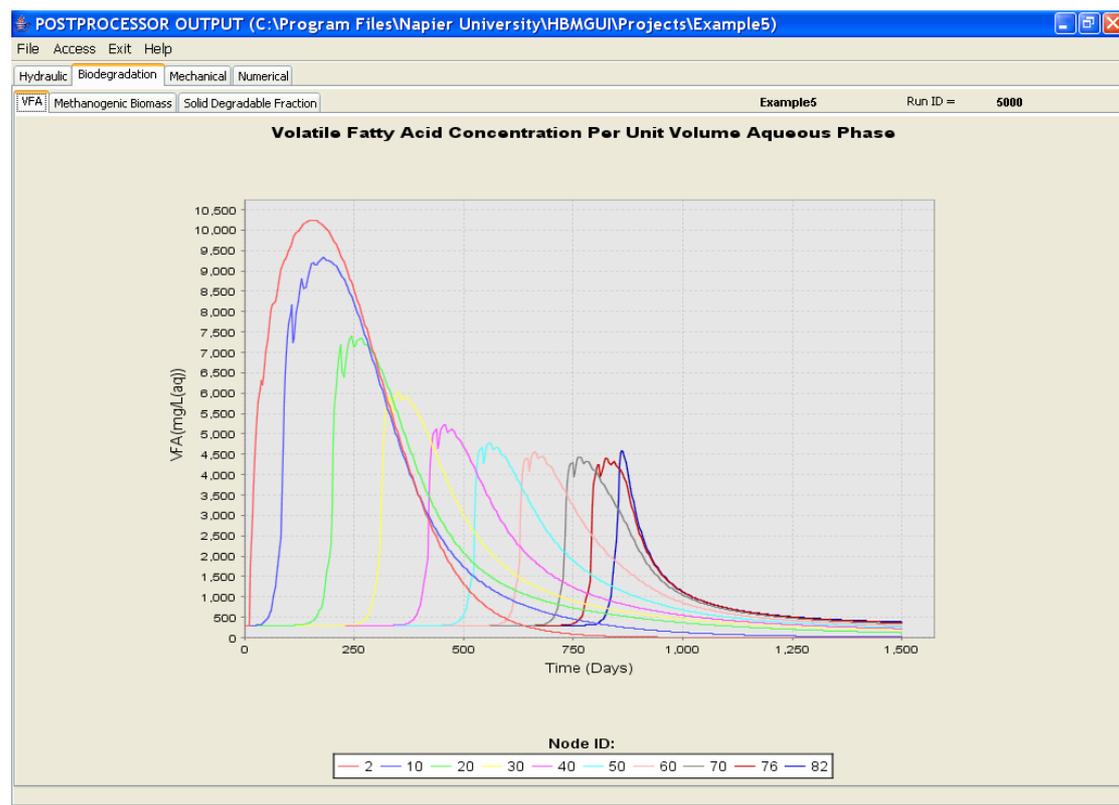


Biodegradation

Evolution of VFA, methanogen biomass and degradable fraction depletion over time is shown in the corresponding sub-panes of the *Biodegradation* pane. The first thing to note about the data in all sub-panes is the impact of the filling, i.e. the staged appearance of each monitored node/element and corresponding activation of the decomposition process.

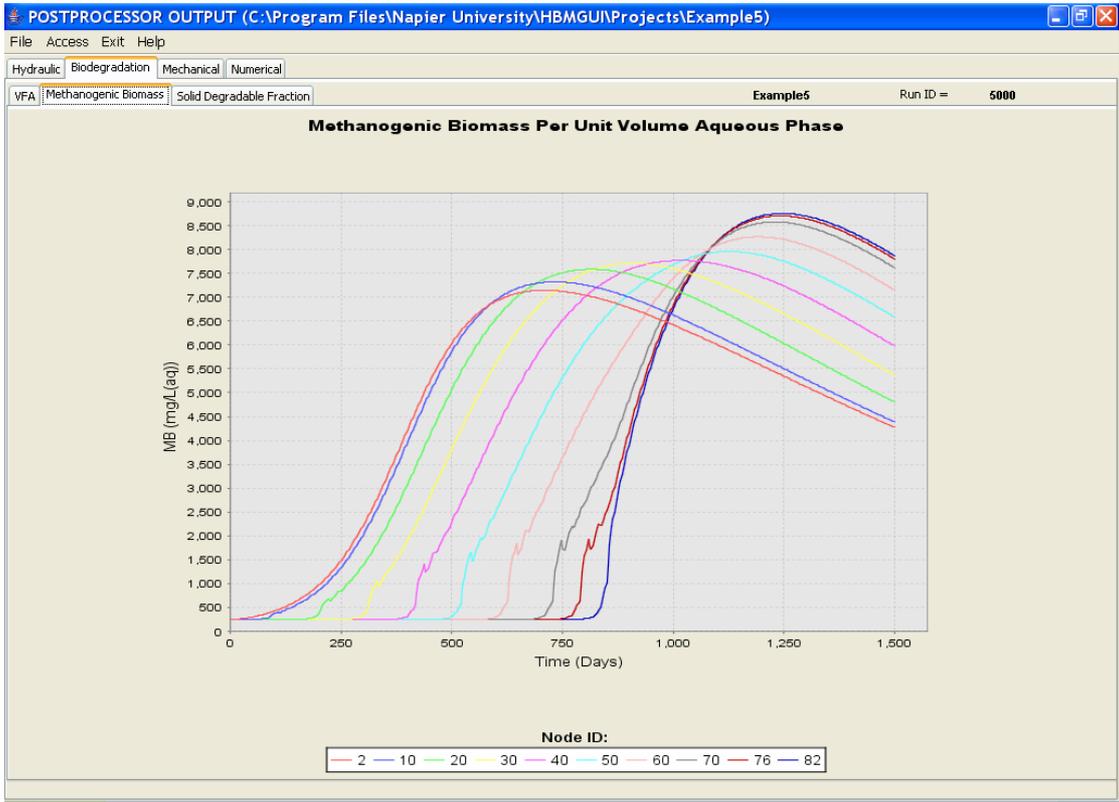
Volatile Fatty Acid

Volatile fatty acids show the familiar rapid rise in the early stages of decomposition. The gradual decline in peak values in latterly disclosed elements is consistent with the influence of methanogens in adjacent elements that diffuse into in the newly disclosed elements and accelerate consumption of VFA therein.



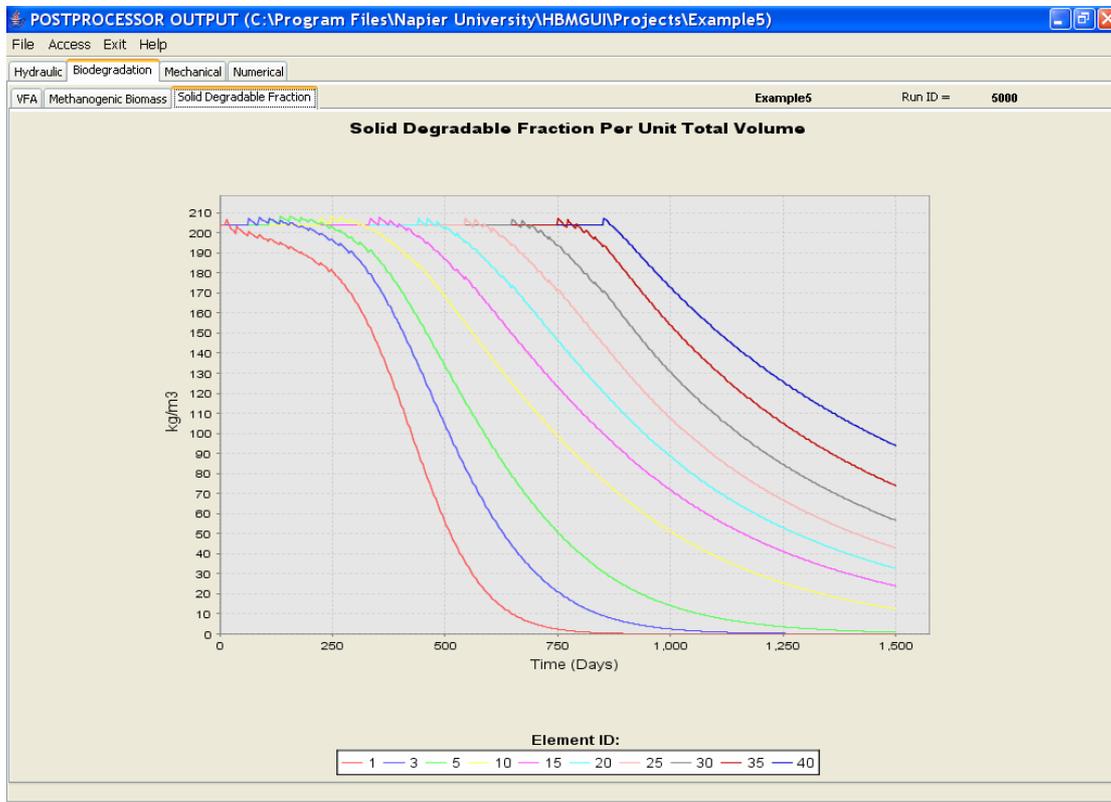
Methanogenic biomass

It is conceivable that the increasing presence of methanogens diffuse rapidly into newly disclosed elements. There is then a more pronounced increase in biomass in the higher elements, i.e. those elements that disclose amidst relatively high methanogenic biomass concentrations.



Solid degradable fraction

Solid degradable fraction data reveals increases in density due to load-related compression. Subsequent behaviour of each trace is then a function of local moisture content (high in element 1) and other controlling factors. For example, there is a large methanogenic biomass in the latterly disclosed elements hence little evidence of a deceleration in the rate of decomposition due to product inhibition. At the end of the simulation, the progress of decomposition is clearly related to the spatial distribution of moisture and the staged infilling.

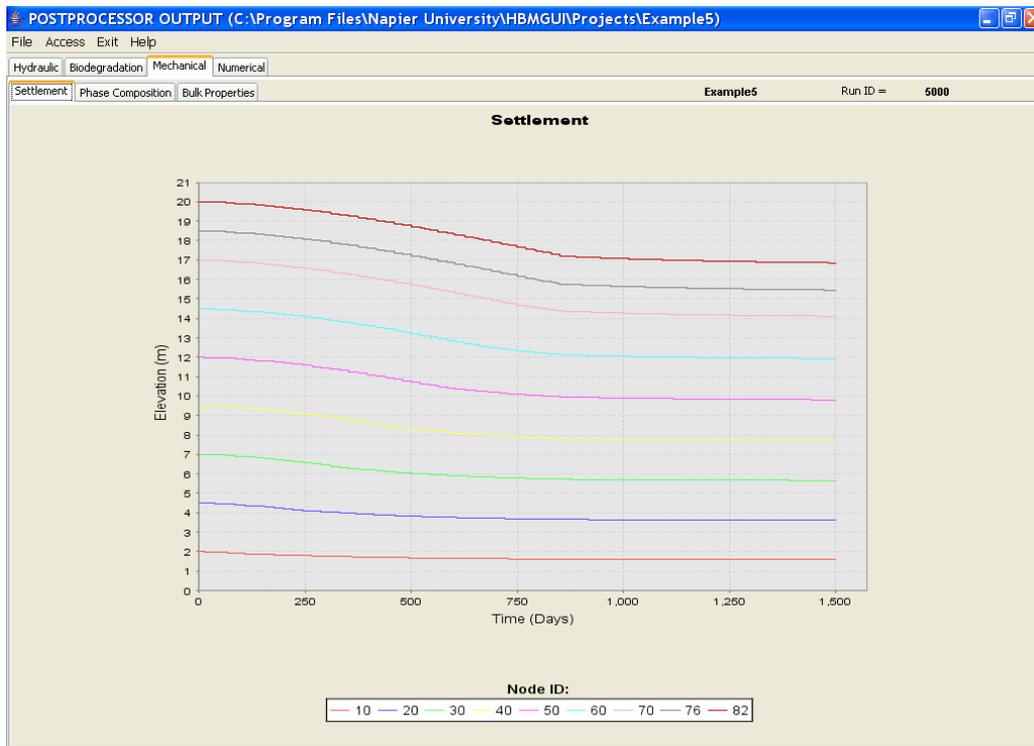


Mechanical

Settlement

Displacements for all specified nodes are reported in the *Settlement* pane. Note, however, that all traces originate from their initial (hidden) elevation. At this stage the waste column is unloaded. On disclosure, each element loads underlying elements. In this case, when the final element is placed, self-weight has compressed the underlying 39 elements to a height of about 16 m. The surface of the final element⁷ eventually (at 1500 days) lies at an elevation of 16.86 m.

⁷ In reality filling continues up to some overfilled level, which for this scenario would mean more than 20 m of unloaded waste. To simulate a filling to a pre-determined level, it is necessary to overfill and allow self-weight compression to bring the column to the required height within a given period of time. Post closure settlements are then based on a more realistic waste profile. Through this type of simulation, we can more rationally estimate the amount of waste to be imported and settlement to final grade level.



Phase composition

The extent to which changes in the decomposable fraction influence waste phase composition is also shown in the Phase Composition sub-pane of the Mechanical pane.

The phase composition is shown for Element 1 on the days specified under Graphics Output Control.

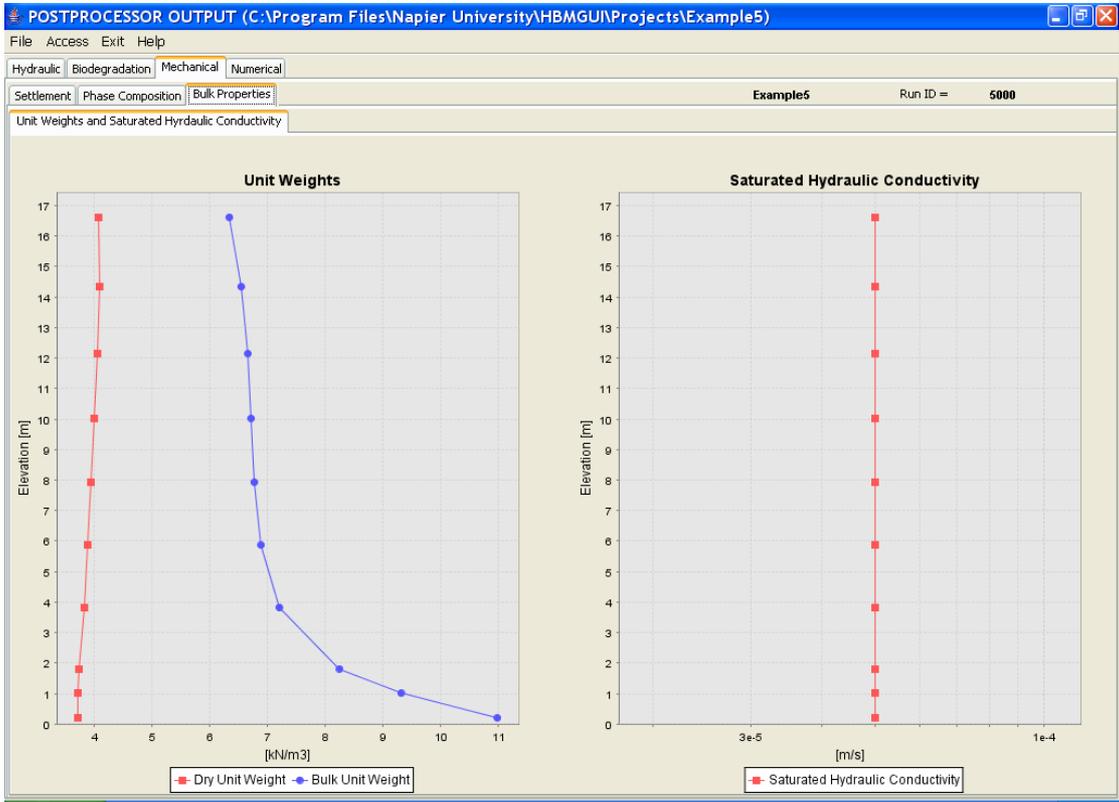
In contrast to a conventional geotechnical soil model, the phase composition here relates to a four phase material. It may be noted that there is:

- no change in solid inert volume,
- decomposable volume is removed by biodegradation,
- although loss of decomposable volume induces a change in void volume, reductions in void volume are also caused by mechanical creep, and
- moisture volume is determined by the unsaturated flow analysis with moisture retention parameters dependent on phase composition.

Bulk Properties

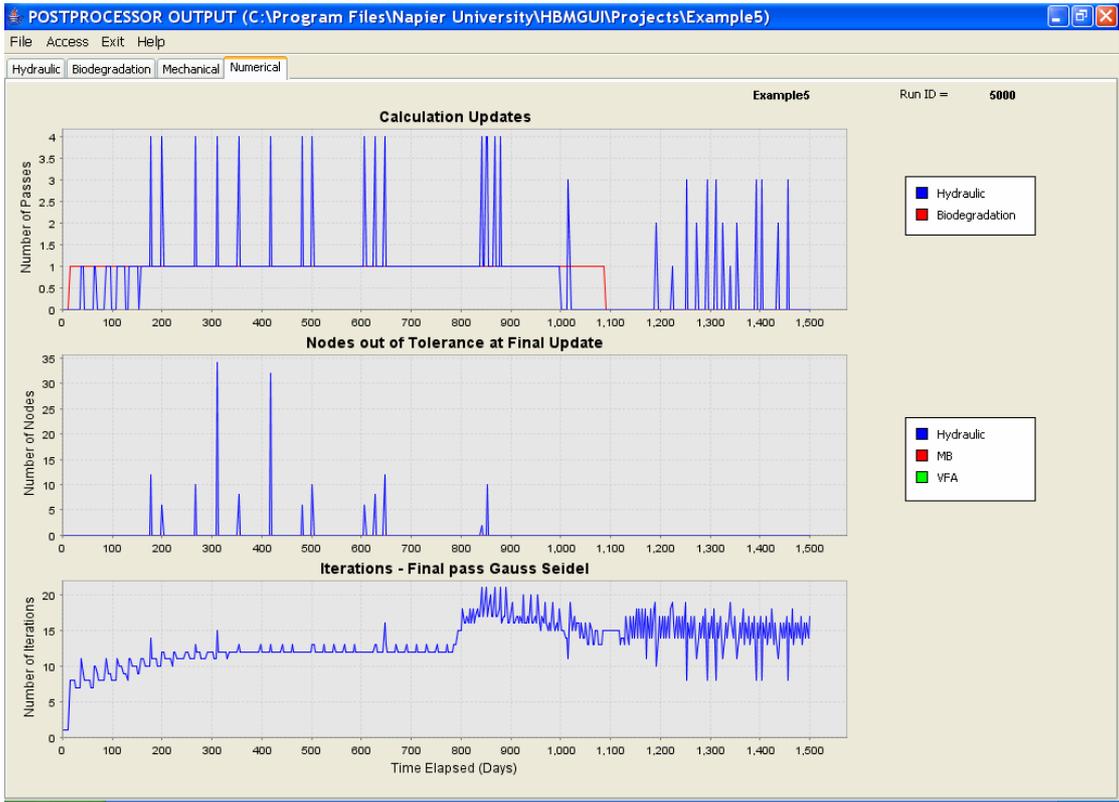
Unit weights & Saturated Hydraulic Conductivity

The bulk and dry unit weight profiles for this example indicate decomposition throughout the column with greater solids loss at the base. Interestingly the combined effect of self weight and decomposition has produced a dry unit weight profile with a relatively narrow range of values, arguably much narrower than would normally be anticipated.



Numerical

The numerical performance data clearly reflect disclosure perturbations but also indicate a rapid return to more comfortable and stable solution performance.



Example 6: Waste Column with Filling & Fixed Initial Moisture Content: Moisture Effects, Biodegradation & Settlement, Raw Water Infiltration

Project directory is Example6

This example demonstrates the simulation of waste filling combined with infiltration. The problem is idealised as a waste column, 20m high when unloaded, with initial volumetric moisture content of 0.3. Filling is depicted by a process of element placement over a period of about 850 days; total simulation period is 1500 days. It is a variation on Example 5, differing only by the addition of 50 mm/day of raw water over two separate 7 day periods. Moisture redistribution, biodegradation and settlement are followed during filling and for about 650 days thereafter.

To Start the New Example

- ✦ Start the GUI using the desktop icon.

From the Open Project file chooser, a number of options exist. This example can be:

- a) Built from scratch following the input instructions of Example 5 and the additional model building described below. Open a new project directory
- b) As an extension Example 5, whereby only the additional model building described below is undertaken. Open *Example5* (or your previously defined project name).
- c) By following the previously built model. Open *Example6*.

Entry to the Preprocessor is on the *General and Time* pane.

MODEL BUILDING - PREPROCESSOR

Boundary Conditions

Infilling & Infiltration

Infiltration events occur in two periods of 7 days, days 200 – 206 and 1000 – 1006. Influent water quality characteristics in the form of VFA and MB concentrations are entered in columns 3 & 4. For the case of raw water, set VFA = 0 and MB = 0.

- ✦ Complete the infiltration table as follows:

Day	Infiltration (mm)	VFA	MB
200	50	0	0
...
206	50	0	0
1000	50	0	0
...
1006	50	0	0
10000	50	0	0

Note that dummy termination data is required to avoid end of file errors.

Graphical output control

In order to investigate more closely the infiltration events, graphical output days have been changed. In this case 12 days are to be monitored:

- ✦ Enter *Number of Days* = 12
- ✦ Enter *Data days* = 100, 199, 205, 300, 400, 500, 600, 700, 800, 999, 1005, 1250 (No commas)

SOLUTION

The prepared model must be saved and HBM input data files created by clicking on WRITE DATA

If this Example has been built by modifying the model of Example 5, then the correct initial hydraulic conditions will have been stored by the model. If you have built this from scratch, then an initialise moisture analysis is required and you must now refer to the relevant sections of Example 5.

OUTPUT - POSTPROCESSOR

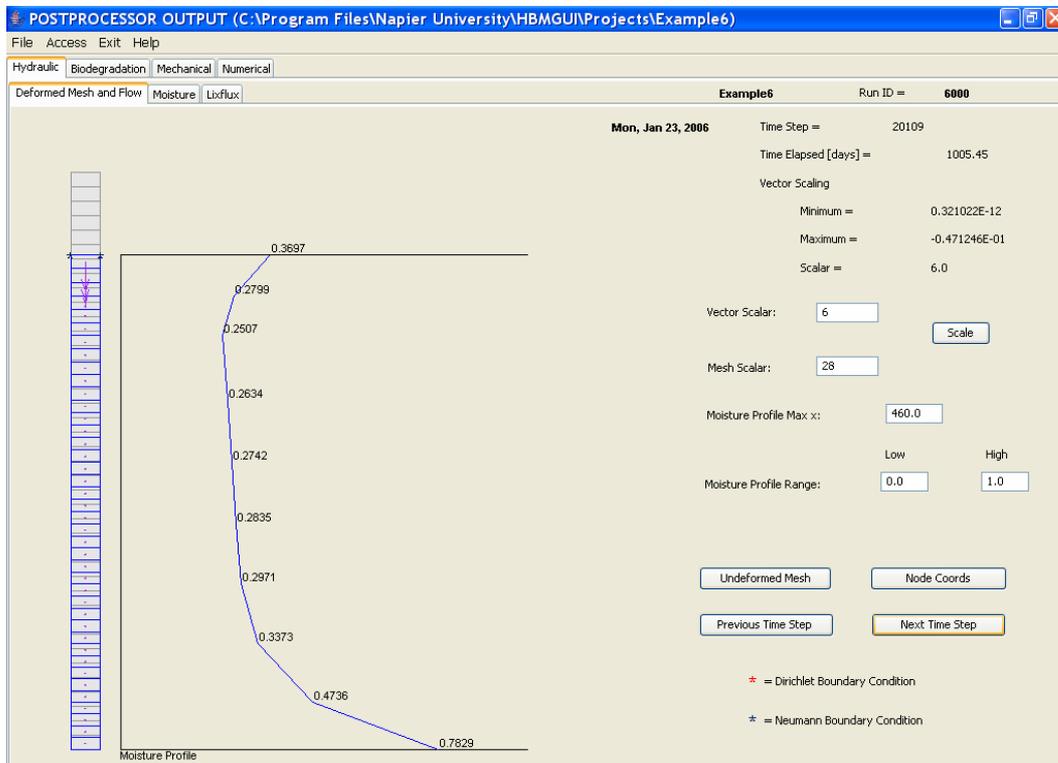
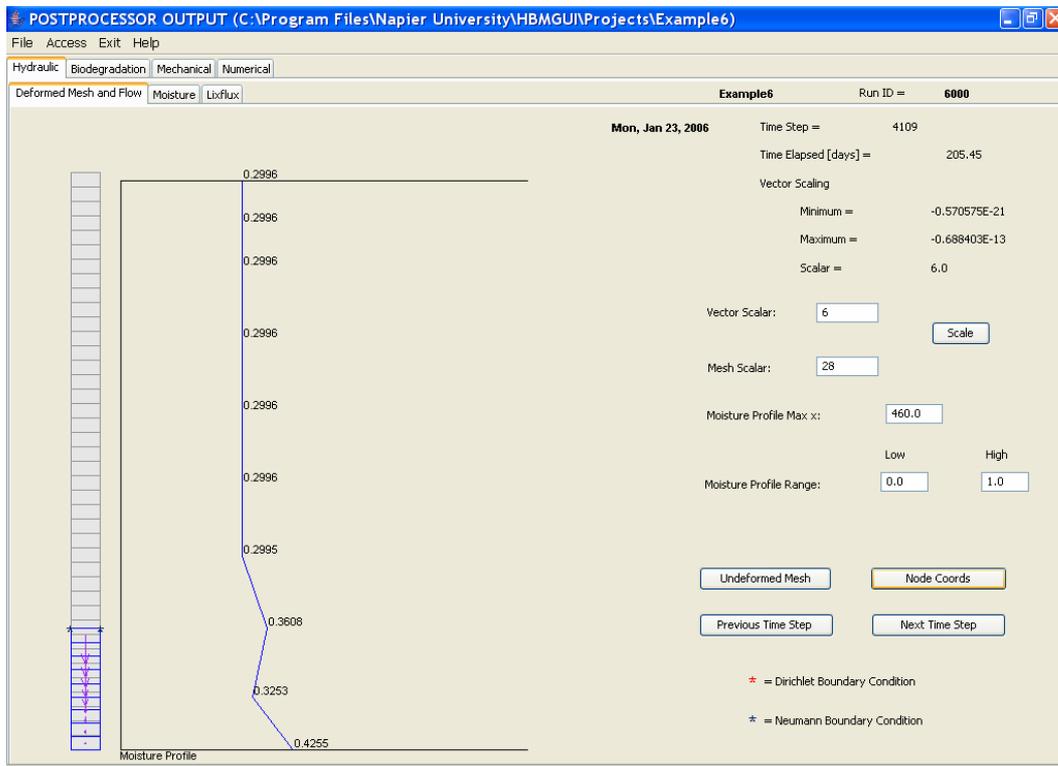
Hydraulic

Deformed mesh & flow

The deformed mesh, flow vectors and moisture profile plots need to be resized using the on-screen view and range scaling factors:

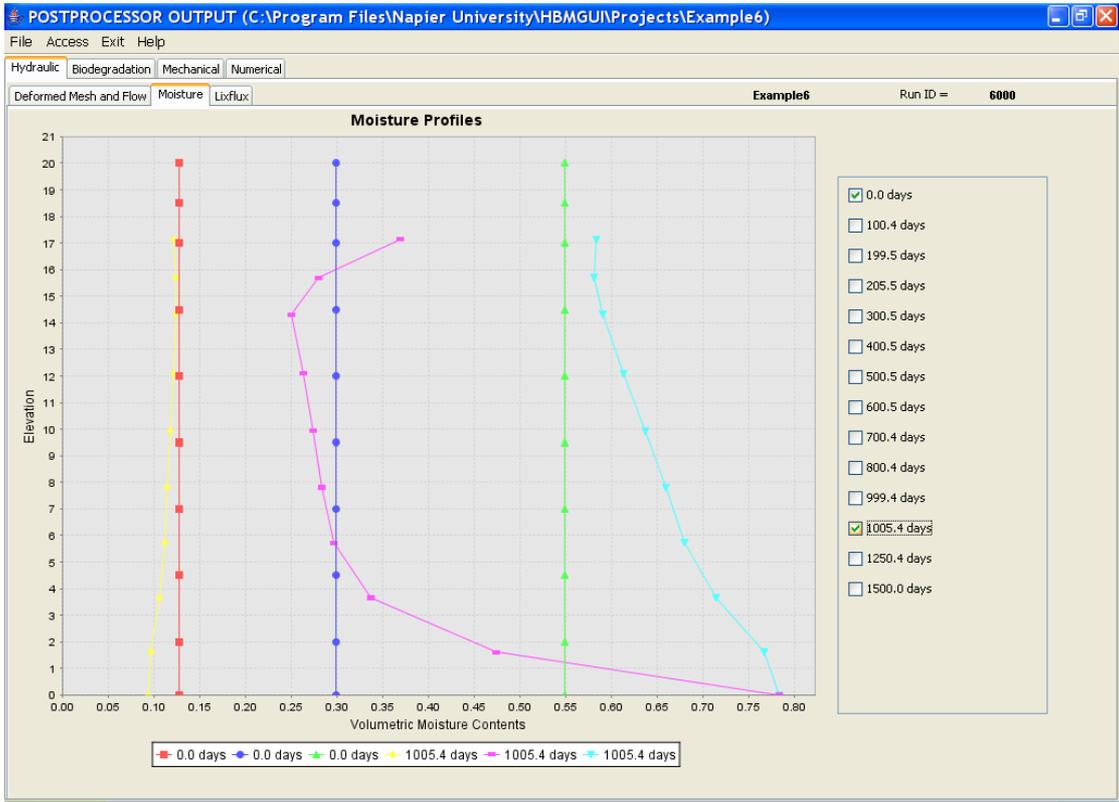
- ✦ Set *Mesh Scalar* = 28 and a *Vector Scalar* = 6
- ✦ Click on *Scale* button.

The figures below, obtained by clicking repeatedly on *Next Time Step*, show the waste column during the first infiltration event (day 205), second infiltration event (day 1005) and the end of the simulation. Remember that during filling, the moisture contents shown in the moisture profile diagram at elevations higher than the visible mesh (see day 205) correspond to hidden elements. On disclosure, the initial volumetric moisture content of 0.2996 is redistributed according to the local contemporaneous hydraulic regime.



Moisture

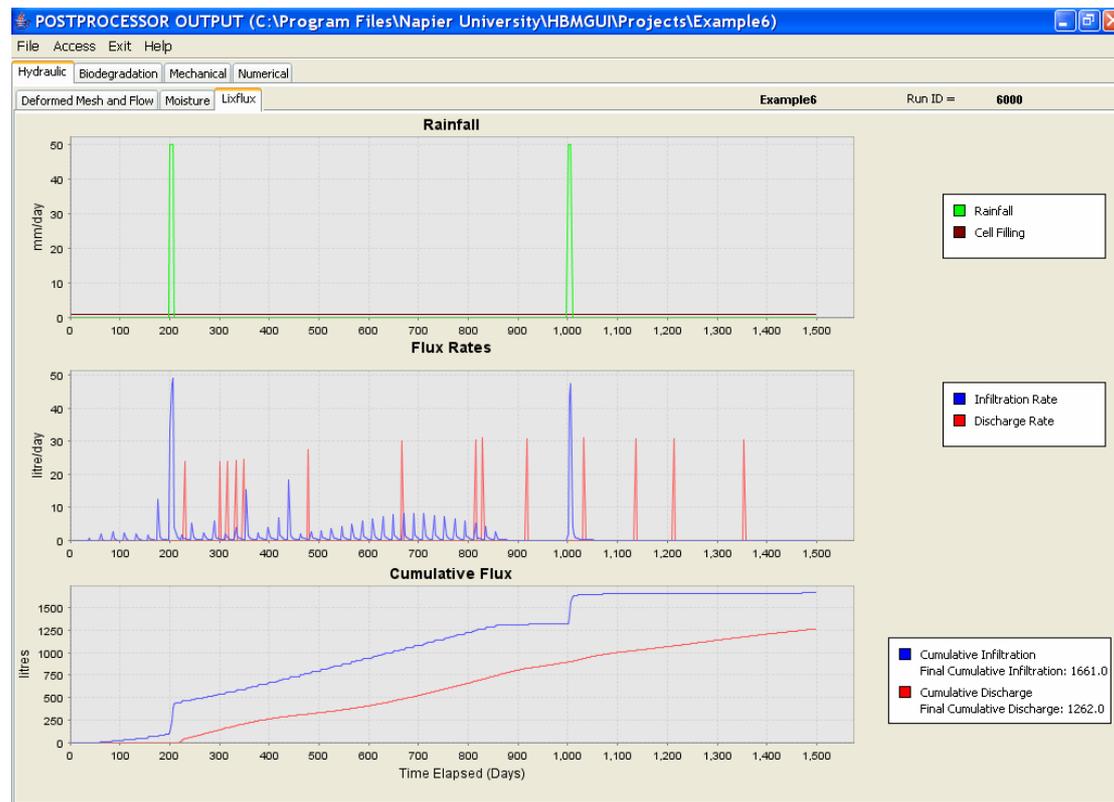
As in Example 5, the combined effect of initial moisture content, infiltration, and the equilibrium moisture profile, on redistribution is well illustrated in the moisture plots. Observe again, the zones of drainage and absorption delineated by the actual moisture profile for day 1005 relative to initial condition. Also note the distinct wetting front in the upper elements.



Lixflux

In this simulation, the two infiltration events introduce 700 litres over the metre square plan area of the column⁸. They are clearly and accurately reported in the flux rate (centre) plot, with traces rising sharply towards 50 mm/day on the days in question (days 200-206 & 1000-1006). Also evident is redistributive drainage recorded in the newly disclosed elements and reported as infiltration.

Drainage occurs from the column base shortly before day 200, although corresponding discharge rates are again inconsistent with the cumulative flux.



⁸ 50 mm/day x 1 m x 14 days = 700 litres

Biodegradation

Examination of all three of the biodegradation output data plots, indicate the occurrence of the infiltration events. Flushing is particularly evident in the methanogenic biomass plot. However, the impact of flushing appears to be relatively short-lived with no significant long-term influence on the progress of decomposition.

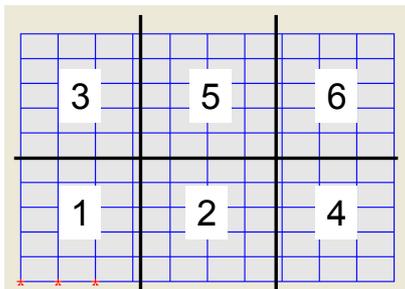
Mechanical

The application of the infiltration event appears to have little impact on the long-term settlement or unit weight profiles of the waste column.

Example 7: Two Dimensional Homogeneous Landfill Section with Cellular Filling: Moisture Effects, Biodegradation & Settlement

Project directory is Example7

This example illustrates the ability of the HBM model to simulate filling on a cellular pattern. There is no infiltration and we have not attempted to demonstrate any form of mass balance in this simulation. It uses the two-dimensional landfill section of Example 1; the only difference between Example 1 & 7 is the specification of the fillable element codes and the filling pattern.



MODEL BUILDING - PREPROCESSOR

Material Properties

- ✦ Click on *Material Properties* pane tab.

Building 'from scratch', add a material property set.

- ✦ Click on *Add Set*: A dialog box appears.
- ✦ Select the *Biodegradable* option, then click on *OK*.

A set of (biodegradable) waste material properties appears. Under *Basic* access (default), only *Material Property Set* number the *Initial Solid Degradable Fraction* and *Bulk Unit Weight (as placed)* are defined. All other material properties are inaccessible (greyed out) until the advanced option is selected.

Infilling - disclosable elements

The procedure for defining fillabel elements is described under Example 5. What follows is a summary of the Material Property Table settings.

- ✦ Set *Material Property Set Number* = 4
- ✦ Click on *Add Set*: A dialog box appears.
- ✦ Select the *Biodegradable* option, then click on *OK*.
- ✦ Set *Material Property Set Number* = 9
- ✦ Modify selected material property set values for set 9 as given by the table in Appendix 1.

Note that is it necessary to change access level from basic to advanced to make these changes.

- ✦ Return to the Geometry pane to check that all elements in the Element Assignment Table are assigned the element material property set number, i.e. 4, in right hand column.

Boundary Conditions

Infilling & Infiltration

For simplicity, the filling pattern depicts only 6 section sub-cells. Sub-cells are defined by the positions of their bottom left and top right corners in the finite element mesh coordinate system. The fill rate reflects the rate at which the level of waste gradually rises within a particular cell; we have chosen 0.1 m/day for all cells but this value could be different in each. Recall that the two-dimensional mesh is 30 wide by 20m high. The six sub-cells and pattern of filling are shown in the figure above.

To define this infilling scheme:

- ✦ Click on *Add Subcell* to create 6 cells.
- ✦ Complete the infilling table as follows:

Subcell	x1	y1	x2	y2	Fill rate
1	0	0	10	10	0.1
2	10	0	20	10	0.1
3	0	10	10	20	0.1
4	20	0	30	10	0.1
5	10	10	20	20	0.1
6	20	10	30	10000	0.1

The value of 10,000 is added to the final cell upper y coordinate as a dummy variable and to avoid an end of file error.

SOLUTION

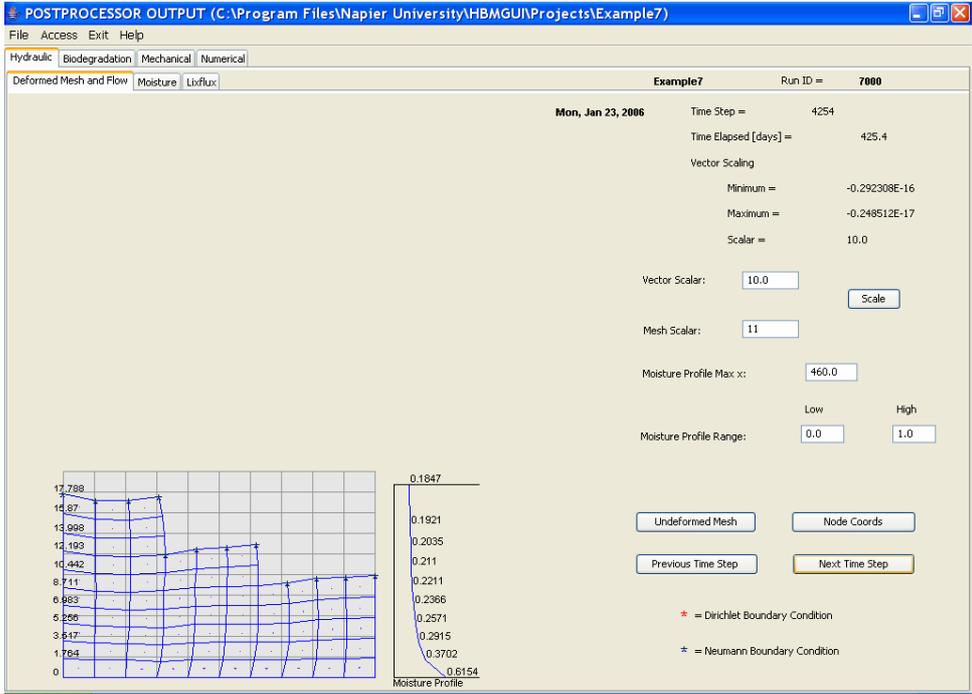
The prepared model must be saved and HBM input data files created by clicking on WRITE DATA

OUTPUT - POSTPROCESSOR

Hydraulic

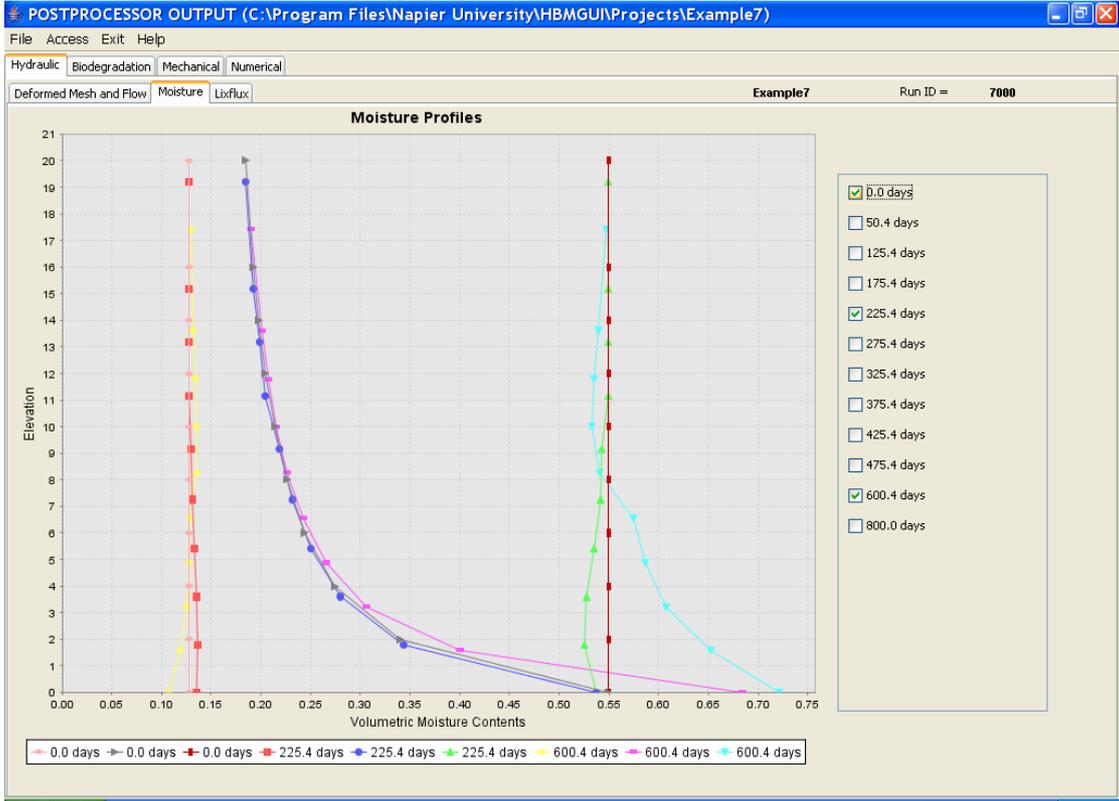
Deformed mesh & flow

By advancing through the sequence of deformed mesh plots, the progress of infilling can be observed. The two dimensional nature of the mechanical model is evident from the element deformations. The figure below reproduces deformations for the visible mesh on day 425.



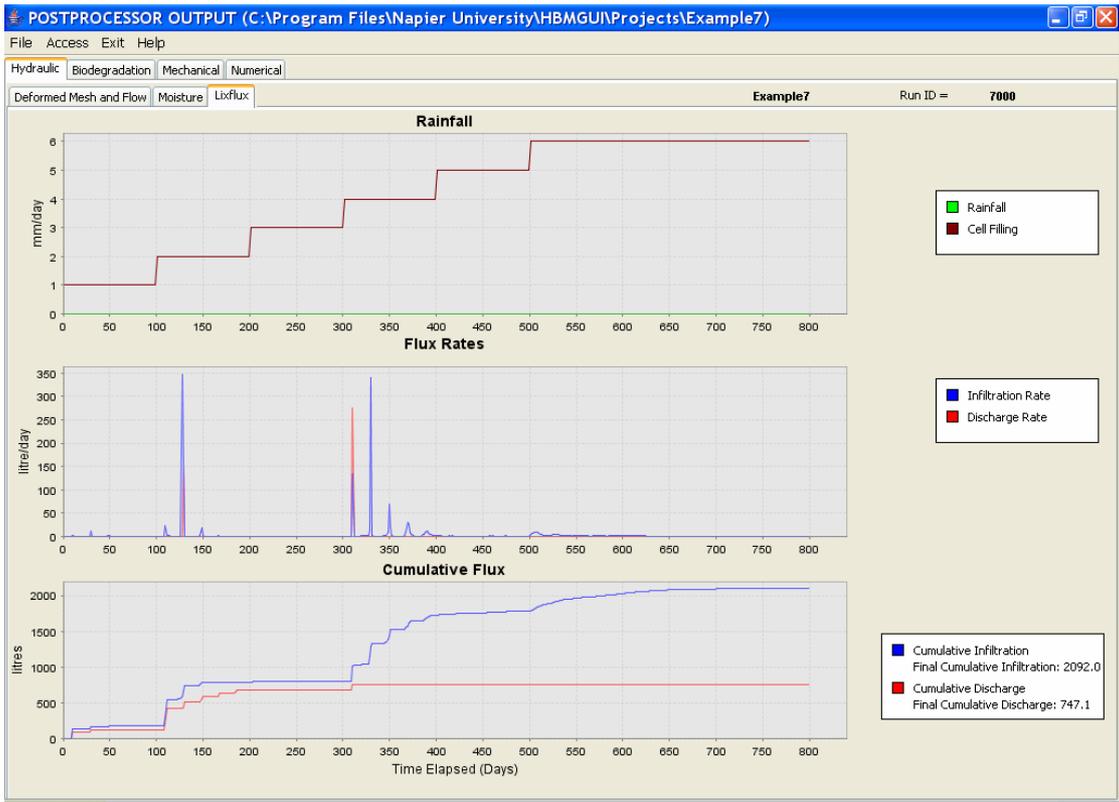
Moisture

Observe in the moisture profiles plot the combined influence of cellular filling and decomposition on the saturated volumetric moisture content. At 225 days, only the lower elements are present and reveal reduced saturated moisture contents due to self-weight compression. At 600 days, the upper elements have been disclosed and show similar reduced saturated moisture content due to self-weight. The underlying elements, however, reveal an increase in saturated moisture content due to decomposition.



Lixflux

Observe the cell filling staircase in the upper lixflux plot; this feature is included simply to enable tracking of the infilling process and to allow correlation of cell operations with flow effects.

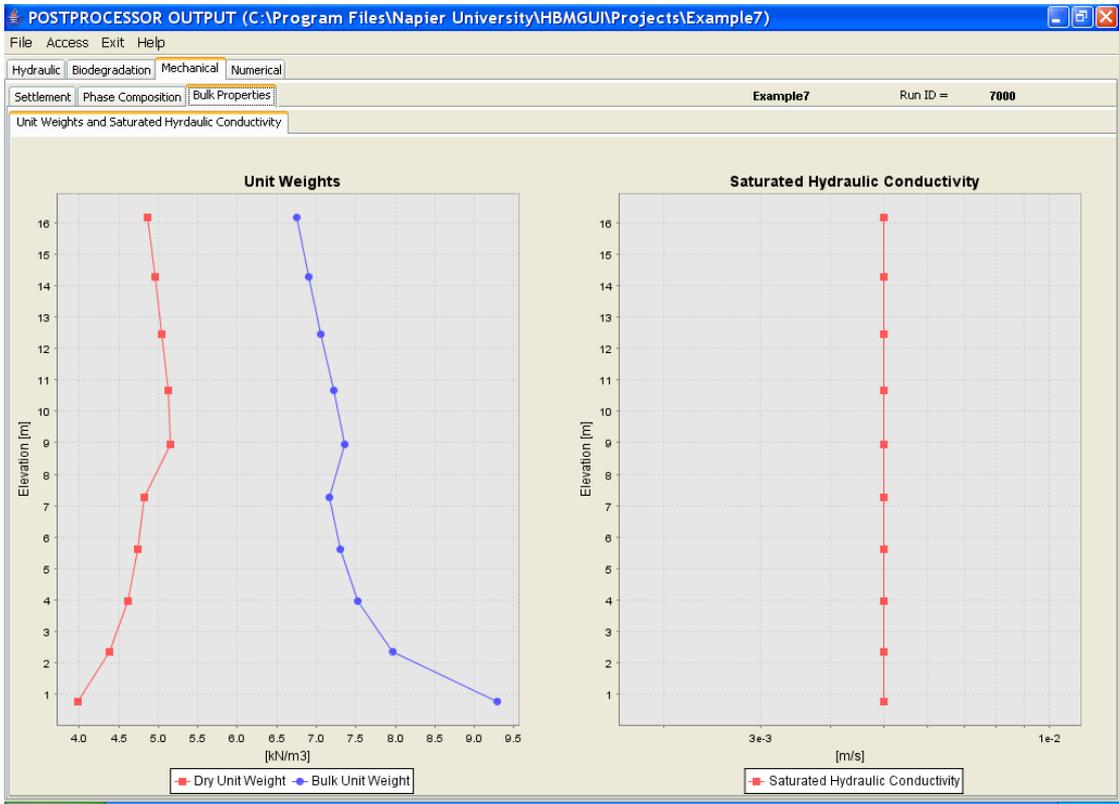


Biodegradation

Observe the staged response of all specified elements and nodes to the infilling process.

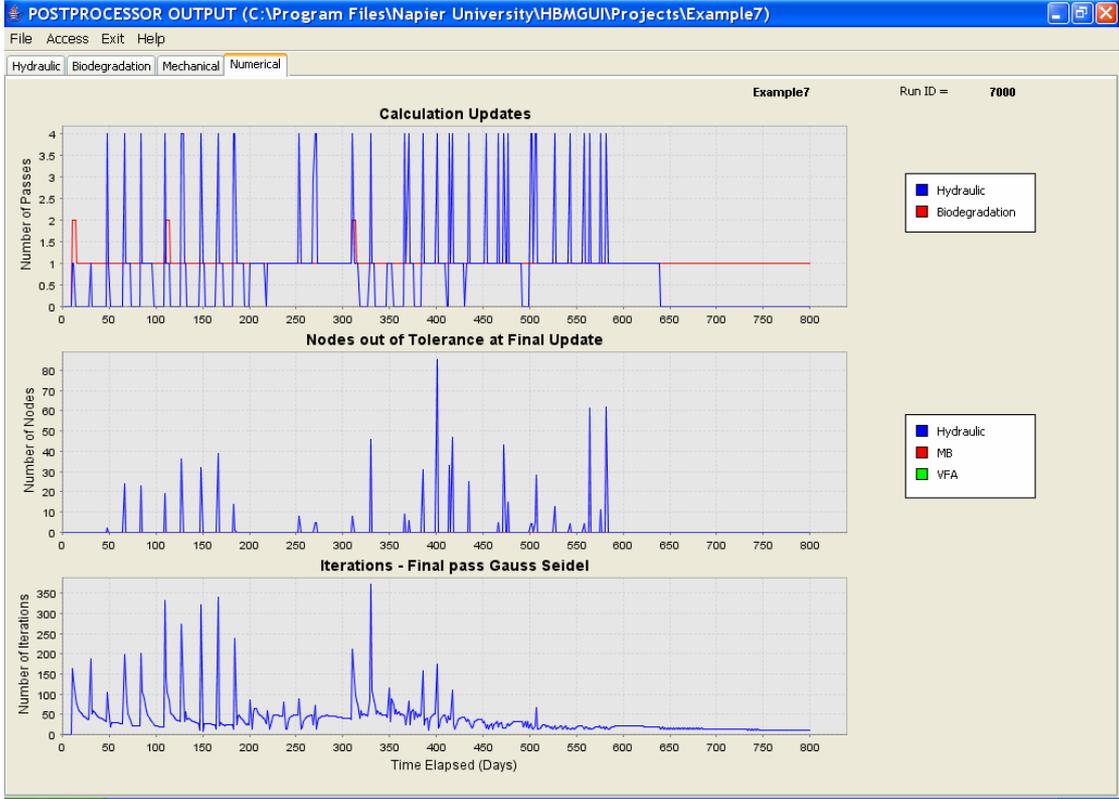
Mechanical

Of particular interest here is the complex combination of effects that have been captured and resolved by the HBM framework in the generation of a dry unit weight profile. In the upper part a steady increase in unit weight with depth due to compression; in the lower, the inclusion of void increase effects due to the longer period of decomposition.



Numerical

Observe here a rather noisy plot. Element disclosure is a perturbation to the numerical solution although any difficulty in finding a solution is only short lived and does not appear to result in any long-term instability or a physically unrealistic solution.



ASSESSING THE SIMULATION & FURTHER DEVELOPMENTS

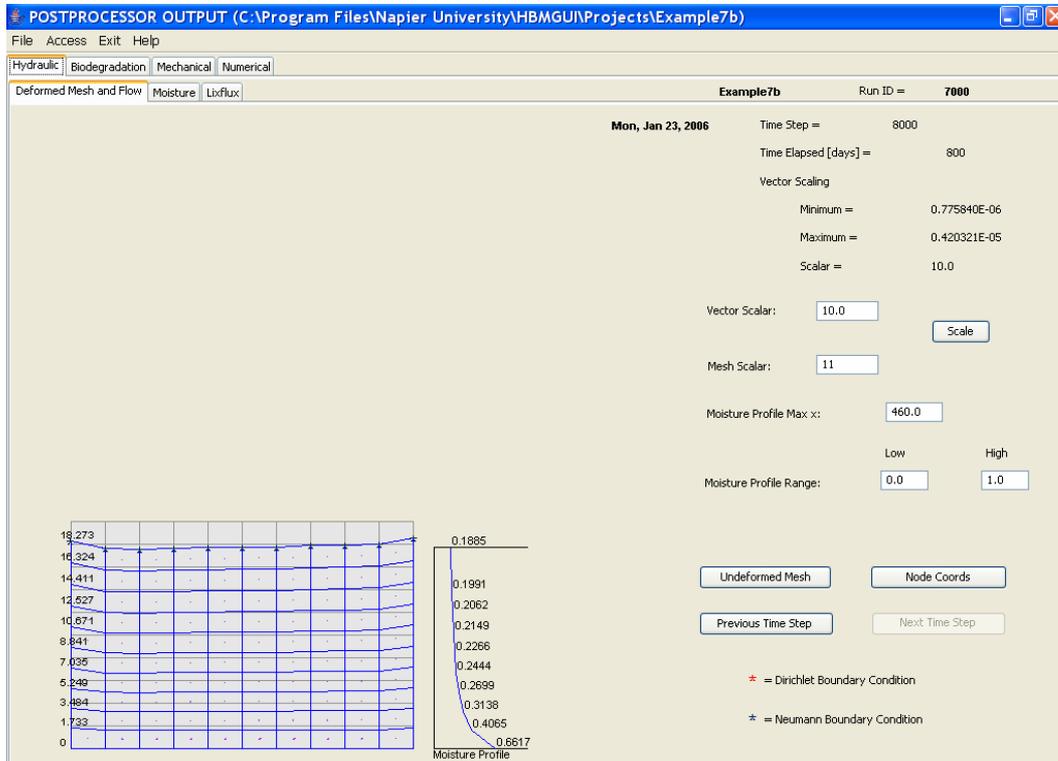
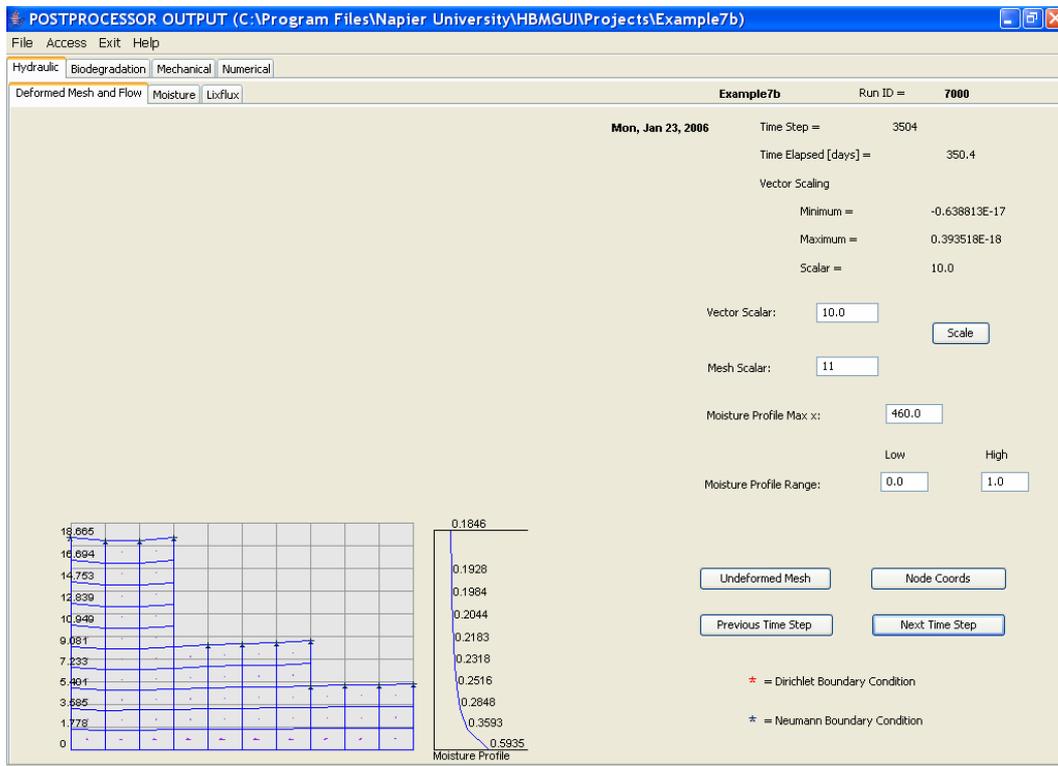
Two-dimensional compression

There are both technical and procedural issues here concerning the displacement of the hidden mesh in advance of disclosure.

Technical considerations include the interpretation of creep and biodegradation induced effects. Additionally, incremental nodal displacements at boundaries, both vertical and sloping require further consideration. That said, it is encouraging to note that at this stage of development, qualitatively plausible deformation patterns are captured.

Procedural considerations concern the plausibility of the observed displacements with respect to on-site behaviour. Within the current mesh, if a one dimensional pattern of displacement is preferred then the horizontal displacement of all nodes can be constrained. This is done in the *Pre-processor, Boundary Conditions, Mechanical Pane*, by applying x-fixities to all rows currently containing zero (by inserting value = 1). This simulation has been run and is included in the examples as Example 7b.

The deformed mesh with all nodes subject to x-displacement fixity for day 350 is shown below. The final deformed shape at the end of the simulation also shown, indicating the uneven nature of settlement that would occur with cellular filling



Appendix 1 – Material Property Sets & Parameters

	Input parameter	Dimensions	Waste	Inert	Hidden
	Material property set		1-8	1-8	9
Hydraulic					
H1	Van Genuchten α		1.4	5	
H2	Van Genuchten n		1.6	5	
H3	Residual moisture content (w/w)		0.25		
H4	Specific storage		0		
H5	Saturated hydraulic conductivity	$\text{m}\cdot\text{s}^{-1}$	5×10^{-5}	1×10^{-2}	5×10^{-15}
H6	Ratio: vert. to horiz. conductivity		1		
Biodegradation					
B1	Maximum hydrolysis rate	$\text{g}\cdot\text{m}^{-3}_{(\text{aq})}\cdot\text{day}^{-1}$	2500	0	0
B2	Product inhibition	$\text{m}^3\cdot\text{g}^{-1}$	2×10^{-4}		
B2	Digestibility		0.7		
B3	Half rate	$\text{g}\cdot\text{m}^{-3}$	4000		
B5	Methanogen growth	day^{-1}	0.02	0	0
B6	Methanogen death	day^{-1}	0.002	0	0
B7	Yield coefficient		0.08		
B8	Diffusion coefficient	$\text{m}^2\cdot\text{day}^{-1}$	0.05		0.005
I1	Initial solid degradable fraction		0.4	0.01	0.4
I2	Initial VFA concentration	$\text{g}\cdot\text{m}^{-3}$	300	0	
I3	Initial methanogenic biomass	$\text{g}\cdot\text{m}^{-3}$	250	0	
Mechanical					
M1	Elastic stiffness		0.072	0.02	
M2	Elastoplastic stiffness		0.23	0.1	
M3	Poisson's ratio		0.35		
I4	Initial yield stress	kPa	30	100	
M4	Creep viscosity		0.0015	0.0002	
M5	Decomposition-induced void		-0.65		
M6	Decomposition hardening	kPa	2		
I5	Dry unit weight (as placed)	$\text{kN}\cdot\text{m}^{-3}$	5		
M7	Inert phase particle weight	$\text{kN}\cdot\text{m}^{-3}$	17		
M8	Degradable phase particle weight	$\text{kN}\cdot\text{m}^{-3}$	7.3		