Model created in COMSOL Multiphysics 6.4

The Mandel–Cryer Effect

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Introduction

Cryer's problem is a three-dimensional consolidation benchmark where a porous sphere is subjected to a uniform boundary pressure. The pore pressure at the center of the sphere rises due to the Mandel–Cryer effect, which is captured by a bidirectional coupling between Darcy's Law and Solid Mechanics interfaces through use of the Poroelasticity multiphysics interface.

In its initial state, the sphere is not deformed and only subject to ambient atmospheric pressure. The sudden load increase on the surface is instantly affecting the pore pressure, while the solid needs time to deform. The pore fluid is squeezed out of the outer layers, first, so they act like a tightening belt. This leads to a pressure increase in the center, where it even exceeds the value of the applied load. Due to drainage the pressure then gradually decreases toward a new equilibrium state.

Model Definition

In the case of small deformations, there is an analytical solution for Cryer's problem that describes the pressure p (normalized with the pressure load p_0) at the center of the sphere as a function of the bulk modulus K, shear modulus G, Biot's coefficient α_B, permeability κ, fluid viscosity μ_f, and storage porosity S_p:

$$\frac{p}{p_0} = 2m\sum_{i=1}^{\infty}\frac{\sin z_i - z_i}{m z_i \cos z_i + (2m-1)\sin z_i}\exp\left(\frac{z_i^2 c_v t}{\beta a^2}\right) \tag{1}$$

Here z_i are the roots of the nonlinear equation

$$(1 - m z_i^2)\sin z_i - z_i \cos z_i = 0\,, \tag{2}$$

Furthermore, a is the radius of the sphere, and the parameters m and β and the coefficient of consolidation c_v are defined as

$$\begin{aligned} m &= \frac{(K + 0{,}75G)}{4G}\left(1 + K\frac{S_p}{\alpha_B^2}\right) \\ c_v &= \frac{\kappa}{\mu_f}(K + 0{,}75G) \\ \beta &= \alpha_B^2 + (K + 0{,}75G)S_p \end{aligned} \quad . \tag{3}$$

The model is set up using the **Poroelasticity, Solid** multiphysics interface, where the interfaces **Darcy's Law** and **Solid Mechanics** are coupled using the biphasic poroelasticity model. Thus, the solid and fluid constituents of the porous medium are assumed to be incompressible and the storage coefficient S_p is zero. The coupled equation system for solid mechanics and Darcy's law is

$$\begin{aligned} 0 &= \nabla \cdot (FS - (p_A - p_{ref})JF^{-T}) + f_V \\ \nabla \cdot (\rho_f \mathbf{v}_d) &= -\rho_f \frac{\partial J}{\partial t} + Q_m \\ \varepsilon_p(J) &= 1 - \frac{(1 - \varepsilon_{p,0})}{J} \end{aligned} \quad . \tag{4}$$

The deformation gradient $\boldsymbol{F}$ is in general defined as the gradient of the current coordinates with respect to the original coordinates, the Jacobian J is the ratio between the current volume and the initial volume, S is the second Piola–Kirchhoff stress tensor, and f_V is a

volume force. Moreover, p_A is the absolute pressure, which equals the sum of pore pressure and reference pressure $p_A = p_f + p_{ref}$, and Q_m is the mass source term in the Darcy's Law equation and $\mathbf{v}_d$ is the Darcy velocity.

A hyperelastic material is used, which is based on a Neo-Hookean material model.

The original geometry is a sphere but due to symmetry it is sufficient to model a 2D axisymmetric component. A symmetry boundary condition is applied at the bottom edge and a constant boundary load is applied on the surface (see Figure 1).

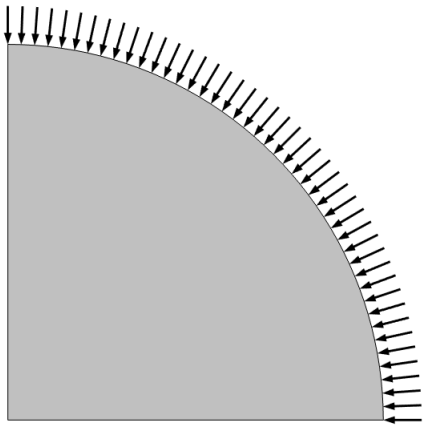

Figure 1: Simplified geometry and prescribed load of the Mandel–Cryer experiment.

The simulation experiment is performed for two different permeability models: for the Kozeny–Carman permeability model and for constant permeability.

Results and Discussion

Figure 2 illustrates the setup: the full spherical geometry and the boundary load, as well as the resulting pore pressure normalized with the pressure load p_0 at the surface of the sphere. The pore pressure increases toward the center of the sphere and reaches a maximum at about 21 s of simulated time which exceeds the outer pressure load by up to 50%.

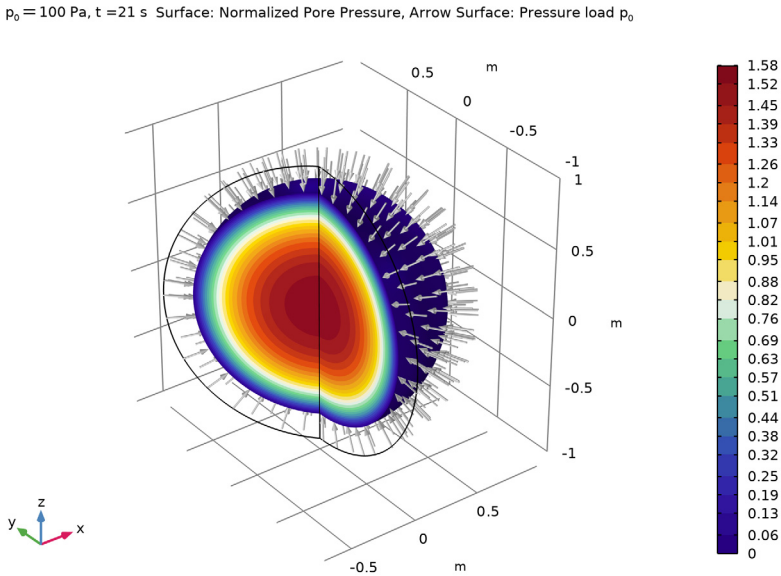

Figure 2: Normalized pore pressure (surface) and prescribed load (arrows) for a pressure load of 1000 Pa after 21 s in the case where the Kozeny–Carman permeability model was used.

Figure 3 and Figure 4 show the pressure, normalized with the external pressure load, as a function of time for the Kozeny–Carman permeability model (Figure 3) and for constant

permeability (Figure 4). In both cases, the Mandel–Cryer effect is correctly represented by the model and the model matches the analytical solution for small deformations.

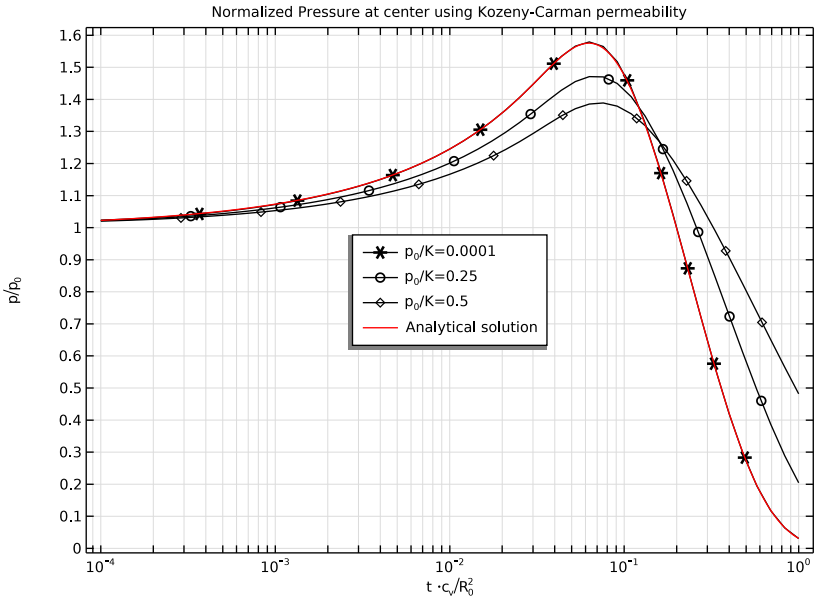

Figure 3: Normalized pore pressure over time at the sphere center for different prescribed loads in the case of Kozeny–Carman permeability.

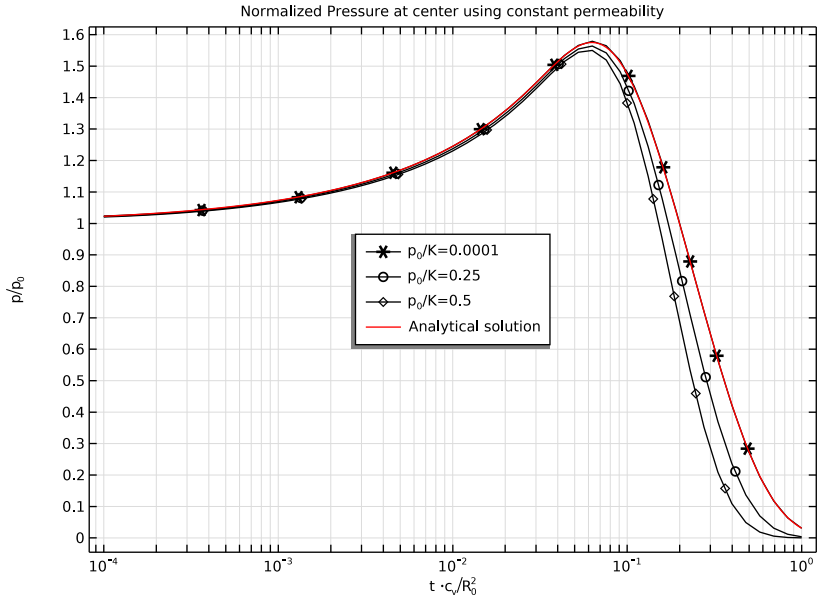

Figure 4: Normalized pore pressure over time at the sphere center for different prescribed loads in the case of constant permeability.

The volume ratio — that is, the ratio of the current pore volume to the initial pore volume — at the center of the sphere is displayed in Figure 5 and Figure 6; for the first case, which

matches the analytical solution, the volume hardly changes, whereas for higher values of boundary pressure large deformation occurs during consolidation.

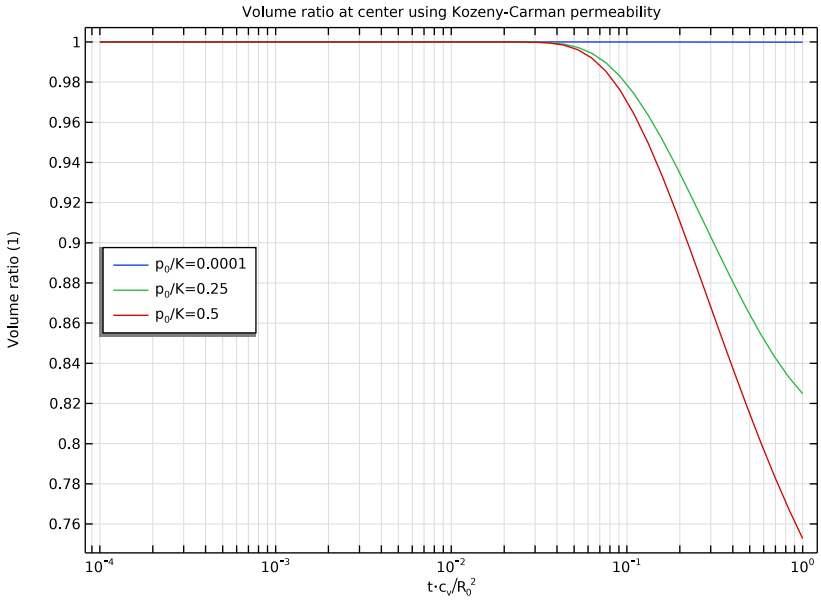

Figure 5: Volume ratio over time at the sphere center for different loads and Kozeny–Carman permeability values.

The two different permeability models seem to differ only in the cases of higher pressure loads where the volume ratio and the normalized pressure decrease more rapidly with time when a constant permeability model is used.

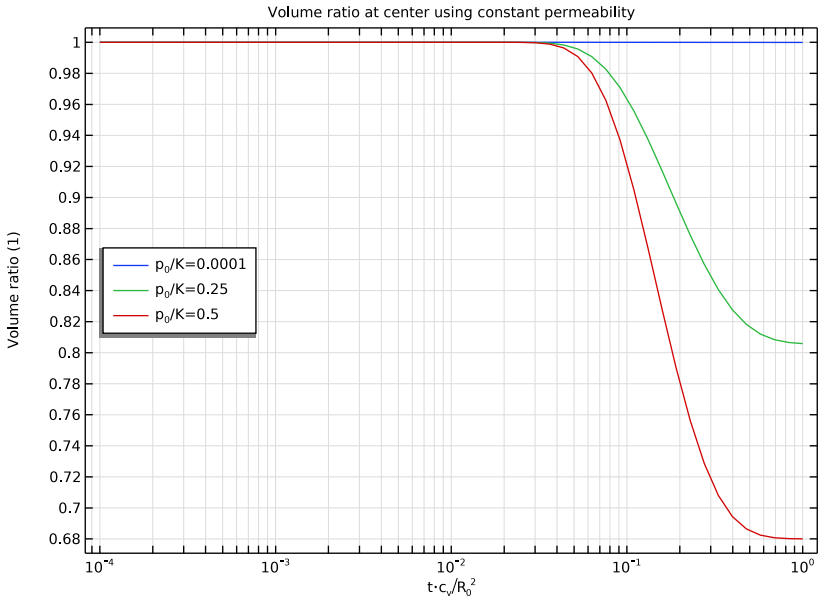

Figure 6: Volume ratio over time at the sphere center for different loads and constant permeability.

References

1. J. Choo, "Large deformation poromechanics with local mass conservation: An enriched Galerkin finite element framework," *Int. J. Numer. Methods Eng.*, vol. 116, no. 1, pp. 66–90, 2018; DOI doi.org/10.1002/nme.5915.

2. A. Verruijt, "Theory of Consolidation," *An Introduction to Soil Dynamics, Theory and Applications of Transport in Porous Media*, vol. 24, pp. 65–90, Springer, Dordrecht, 2009; doi.org/10.1007/978-90-481-3441-0_4.

Application Library path: `Porous_Media_Flow_Module/Verification_Examples/mandel_cryer_effect`

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **2D Axisymmetric**.

2 In the **Select Physics** tree, select **Structural Mechanics** > **Poroelasticity** > **Poroelasticity, Solid**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies** > **Time Dependent**.

6 Click **Done**.

GLOBAL DEFINITIONS

Start by defining the model parameters. You can load them from an external file:

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `mandel_cryer_effect_parameters.txt`.

5 In the table, enter the following settings:

Name	Expression	Value	Description
mv	1/(K0+4/3*G0)	3.3333E-7 1/Pa	Vertical compressibility of the soil in the case of lateral confinement
kappa0	cv*muf*mv	1E-12 m²	Initial permeability
dp	sqrt(180*kappa0*((1-poro0)^2/poro0^3))	1.8974E-5 m	Particle diameter

GEOMETRY 1

Circle 1 (c1)

1 In the **Geometry** toolbar, click **Circle**.

2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.

3 In the **Radius** text field, type `R0`.

4 In the **Sector angle** text field, type `90`.

5 Click **Build Selected**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar.

MATERIALS

In the next step, define the porous material as empty material node; as soon as the physics has been defined the material node's context menu will show you which properties are needed for the simulation. You can then just fill in the values defined in the **Parameters** list.

Porous Material 1 (pmat1)

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **More Materials** > **Porous Material**.

SOLID MECHANICS (SOLID)

Now set up the physics. Start with the **Solid Mechanics** node.

Hyperelastic Material 1

1 In the **Physics** toolbar, click **Domains** and choose **Hyperelastic Material**.

2 Select Domain 1 only.

Symmetry Plane 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry Plane**.

2 Select Boundary 2 only.

Boundary Load 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Boundary Load**.

2 Select Boundary 3 only.

3 In the **Settings** window for **Boundary Load**, locate the **Force** section.

4 From the **Load type** list, choose **Pressure**.

5 In the p text field, type `p0`.

DARCY'S LAW (DL)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Darcy's Law (dl)**.

2 In the **Settings** window for **Darcy's Law**, click to expand the **Discretization** section.

3 From the **Pressure** list, choose **Linear**.

Change the shape function to linear to reduce the computational time and to increase numerical stability, especially for higher pressure load values.

4 Click to collapse the **Discretization** section.

Symmetry 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.

2 Select Boundary 2 only.

Outlet 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Outlet**.

2 Select Boundary 3 only.

3 In the **Settings** window for **Outlet**, locate the **Boundary Condition** section.

4 From the **Boundary condition** list, choose **Pressure**.

Porous Medium: Kozeny-Carman

1 In the **Physics** toolbar, click **Domains** and choose **Porous Medium**.

2 Select Domain 1 only.

3 In the **Settings** window for **Porous Medium**, type `Porous Medium: Kozeny-Carman` in the **Label** text field.

Porous Matrix 1

1 In the **Model Builder** window, click **Porous Matrix 1**.

2 In the **Settings** window for **Porous Matrix**, locate the **Matrix Properties** section.

3 From the **Permeability model** list, choose **Kozeny–Carman**.

4 In the d_p text field, type `dp`.

MULTIPHYSICS

Poroelasticity 1 (poro1)

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Multiphysics** > **Poroelasticity 1 (poro1)** node, then click **Poroelasticity 1 (poro1)**.

2 In the **Settings** window for **Poroelasticity**, locate the **Poroelastic Coupling Properties** section.

3 From the **Poroelasticity model** list, choose **Biphasic**.

4 From the p_{ref} list, choose **Reference pressure level (dl)**.

MATERIALS

Having defined the physics, now fill in the empty expressions in the **Porous Material** node.

Porous Material 1 (pmat1)

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Materials** > **Porous Material 1 (pmat1)** node, then click **Porous Material 1 (pmat1)**.

2 In the **Settings** window for **Porous Material**, locate the **Phase-Specific Properties** section.

3 Click **Add Required Phase Nodes**.

Fluid 1 (pmat1.fluid1)

1 In the **Model Builder** window, click **Fluid 1 (pmat1.fluid1)**.

2 In the **Settings** window for **Fluid**, locate the **Material Contents** section.

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Density	rho	`rhof`	kg/m³	Basic
Dynamic viscosity	mu	`muf`	Pa·s	Basic

Solid 1 (pmat1.solid1)

1 In the **Model Builder** window, right-click **Porous Material 1 (pmat1)** and choose **Solid**.

2 In the **Settings** window for **Solid**, locate the **Solid Properties** section.

3 In the θ_s text field, type `1-poro0`.

Porous Material 1 (pmat1)

1 In the **Model Builder** window, click **Porous Material 1 (pmat1)**.

2 In the **Settings** window for **Porous Material**, locate the **Homogenized Properties** section.

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Lamé parameter μ	muLame	`G0`	N/m²	Lamé parameters
Lamé parameter λ	lambLame	`Lambda0`	N/m²	Lamé parameters
Density	rho	`rhos`	kg/m³	Basic

MESH 1

Free Quad 1

In the **Mesh** toolbar, click **Free Quad**.

Size

1 In the **Model Builder** window, click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Finer**.

4 Click **Build All**.

STUDY 1

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 In the **Output times** text field, type `10^{range(-4,4/50,0)}* R0^2/cv`. This input corresponds to the expected time dependency as shown in Equation 1, enforcing small time intervals in the beginning which are then exponentially growing. The end time of the study time interval is calculated as the square of the sphere radius divided by the coefficient of consolidation.

4 In the **Model Builder** window, click **Study 1**.

5 In the **Settings** window for **Study**, locate the **Study Settings** section.

6 Clear the **Generate default plots** checkbox.

In this case, three different pressure loads are investigated. Therefore, add a parametric sweep.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
p0k (Pressure over bulk modulus)	`0.0001 0.25 0.5`	

5 In the **Model Builder** window, click **Study 1**.

6 In the **Settings** window for **Study**, type `Study with Kozeny-Carman Permeability` in the **Label** text field.

7 In the **Study** toolbar, click **Compute**.

GLOBAL DEFINITIONS

To compare the simulation results with the analytical solution as in Figure 3, you can import the analytical data from an external file provided in the applications database and create an interpolation function.

Analytical Solution

1 In the **Home** toolbar, click **Functions** and choose **Global** > **Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file `mandel_cryer_effect_p_analytical.txt`.

6 In the **Label** text field, type `Analytical Solution`.

7 Locate the **Definition** section. Click **Import**.

8 In the **Function name** text field, type `p_analytical`.

9 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
p_analytical	1

10 In the **Argument** table, enter the following settings:

Argument	Unit
t	s

RESULTS

In the **Model Builder** window, expand the **Results** node.

Grid 1D: Analytical Solution

1 In the **Model Builder** window, expand the **Results** > **Datasets** node.

2 Right-click **Results** > **Datasets** and choose **More Datasets** > **Grid 1D**.

3 In the **Settings** window for **Grid 1D**, type `Grid 1D: Analytical Solution` in the **Label** text field.

4 Locate the **Data** section. From the **Source** list, choose **Function**.

5 From the **Function** list, choose **Analytical Solution (p_analytical)**.

6 Locate the **Parameter Bounds** section. In the **Name** text field, type `t`.

7 In the **Minimum** text field, type `-33.26333`.

8 In the **Maximum** text field, type `366.29667`.

9 Click to expand the **Grid** section. In the **Resolution** text field, type `10000`.

10 From the **Point distribution** list, choose **Mixed uniform/exponential**.

Normalized Pressure (Kozeny-Carman Permeability)

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study with Kozeny-Carman Permeability/ Parametric Solutions 1 (sol2)**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type `Normalized Pressure at center using Kozeny-Carman permeability`.

6 Locate the **Axis** section. Select the **x-axis log scale** checkbox.

7 In the **Label** text field, type `Normalized Pressure (Kozeny-Carman Permeability)`.

8 Locate the **Plot Settings** section.

9 Select the **x-axis label** checkbox. In the associated text field, type `t \cdot \[\mathrm{c_{v} / R_{0}^{2}}\]`, which is LaTex-syntax to write mathematical formulas and expressions.

10 Select the **y-axis label** checkbox. In the associated text field, type `\[\mathrm{p / p_{0}}\]`.

11 Locate the **Legend** section. From the **Position** list, choose **Center**.

Point Graph 1

1 Right-click **Normalized Pressure (Kozeny-Carman Permeability)** and choose **Point Graph**.

2 Select Point 1 only.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

4 In the **Expression** text field, type `p/p0`.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `t/(R0^2/cv)`.

7 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Black**.

8 Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

9 From the **Positioning** list, choose **Interpolated**.

10 Set the **Number** value to **10**.

11 Click to expand the **Legends** section. Select the **Show legends** checkbox.

12 From the **Legends** list, choose **Manual**.

13 In the table, enter the following settings:

Legends
p₀/K=0.0001
p₀/K=0.25
p₀/K=0.5

Normalized Pressure (Kozeny-Carman Permeability)

In the **Model Builder** window, click **Normalized Pressure (Kozeny-Carman Permeability)**.

Function 1

1 In the **Normalized Pressure (Kozeny-Carman Permeability)** toolbar, click **More Plots** and choose **Function**.

2 In the **Settings** window for **Function**, locate the **Data** section.

3 From the **Dataset** list, choose **Grid 1D: Analytical Solution**.

4 Click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Global definitions** > **Functions** > **p_analytical(t) - Analytical Solution**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `p_analytical(t[1/m][s])`.

6 Locate the **x-Axis Data** section. In the **Expression** text field, type `t/(R0^2/cv)`.

7 Select the **Description** checkbox. In the associated text field, type `t(s)`.

8 Click to expand the **Legends** section. Select the **Show legends** checkbox.

9 From the **Legends** list, choose **Manual**.

10 In the table, enter the following settings:

Legends
Analytical solution

11 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Red**.

12 Locate the **x-Axis Data** section. In the **Lower bound** text field, type `1e-4`.

13 In the **Normalized Pressure (Kozeny-Carman Permeability)** toolbar, click **Plot** and compare with Figure 3.

Volume Ratio (Kozeny-Carman Permeability)

Now add a second plot according to Figure 5.

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Volume Ratio (Kozeny-Carman Permeability)` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study with Kozeny-Carman Permeability/Parametric Solutions 1 (sol2)**.

4 Locate the **Plot Settings** section.

5 Select the **x-axis label** checkbox. In the associated text field, type `t\cdot c\[_{\mathrm{v}}/\mathrm{R_{0}}^{2}\]`.

6 Locate the **Axis** section. Select the **x-axis log scale** checkbox.

7 Locate the **Legend** section. From the **Position** list, choose **Middle left**.

Point Graph 1

1 Right-click **Volume Ratio (Kozeny-Carman Permeability)** and choose **Point Graph**.

2 Select Point 1 only.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

4 In the **Expression** text field, type `solid.J`.

5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

6 In the **Expression** text field, type `t/( R0^2/cv)`.

7 Locate the **Legends** section. Select the **Show legends** checkbox.

8 From the **Legends** list, choose **Manual**.

9 In the table, enter the following settings:

Legends
p₀/K=0.0001
p₀/K=0.25
p₀/K=0.5

Volume Ratio (Kozeny-Carman Permeability)

1 In the **Model Builder** window, click **Volume Ratio (Kozeny-Carman Permeability)**.

2 In the **Settings** window for **1D Plot Group**, locate the **Title** section.

3 From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Volume ratio at center using Kozeny-Carman permeability`.

5 In the **Volume Ratio (Kozeny-Carman Permeability)** toolbar, click **Plot**.

MATERIALS

Now add a second study where a constant permeability is used. Therefore, define the permeability in the porous material node.

Porous Material 1 (pmat1)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Materials** > **Porous Material 1 (pmat1)** click **Basic (def)**.

2 In the **Settings** window for **Basic**, locate the **Output Properties** section.

3 Click **Select Quantity**.

4 In the **Physical Quantity** dialog, select **Transport** > **Permeability (m^2)** in the tree.

5 Click **OK**.

6 In the **Settings** window for **Basic**, locate the **Output Properties** section.

7 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Permeability	kappa_iso ; kappaii = kappa_iso, kappaij = 0	kappa0	m^2	3x3

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies** > **Time Dependent**.

4 Click the **Add Study** button in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY WITH CONSTANT PERMEABILITY

1 In the **Settings** window for **Study**, locate the **Study Settings** section.

2 Clear the **Generate default plots** checkbox.

3 In the **Label** text field, type `Study with Constant Permeability`.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study with Constant Permeability** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 In the **Output times** text field, type `10^{range(-4,4/50,0)}* R0^2/cv` as in Study 1.

4 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** checkbox.

5 In the tree, select **Component 1 (comp1)** > **Darcy's Law (dl)** > **Porous Medium: Kozeny-Carman**.

6 Right-click and choose **Disable**.

Now, the default **Porous Medium** node is active, where the constant permeability you have just entered in the material settings will be used.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
p0k (Pressure over bulk modulus)	`0.0001 0.25 0.5`	

5 In the **Study** toolbar, click **Compute**.

RESULTS

Normalized Pressure (Constant Permeability)

1 In the **Model Builder** window, right-click **Normalized Pressure (Kozeny-Carman Permeability)** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study with Constant Permeability/ Parametric Solutions 2 (sol7)**.

4 Locate the **Title** section. In the **Title** text area, type `Normalized Pressure at center using constant permeability`.

5 In the **Label** text field, type `Normalized Pressure (Constant Permeability)`.

6 In the **Normalized Pressure (Constant Permeability)** toolbar, click **Plot**.

Volume Ratio (Constant Permeability)

1 In the **Model Builder** window, right-click **Volume Ratio (Kozeny-Carman Permeability)** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Volume Ratio (Constant Permeability)` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study with Constant Permeability/ Parametric Solutions 2 (sol7)**.

4 Locate the **Title** section. In the **Title** text area, type `Volume ratio at center using constant permeability`.

5 In the **Volume Ratio (Constant Permeability)** toolbar, click **Plot**.

RESULT TEMPLATES

To reproduce Figure 2 follow the steps below.

1 In the **Results** toolbar, click **Result Templates** to open the **Result Templates** window.

2 Go to the **Result Templates** window.

3 In the tree, select **Study with Kozeny-Carman Permeability/Parametric Solutions 1 (sol2)** > **Darcy's Law** > **Pressure, 3D (dl)**.

4 Click the **Add Result Template** button in the window toolbar.

5 In the **Results** toolbar, click **Result Templates** to close the **Result Templates** window.

RESULTS

3D Sphere

1 In the **Results** toolbar, click **More Datasets** and choose **Mirror 3D**.

2 In the **Settings** window for **Mirror 3D**, type `3D Sphere` in the **Label** text field.

3 Click to expand the **Advanced** section. Locate the **Plane Data** section. From the **Plane** list, choose **XY-planes**.

4 Locate the **Advanced** section. Find the **Space variables** subsection. Select the **Remove elements on the symmetry plane** checkbox.

Pressure and Deformation (Kozeny-Carman Permeability)

1 In the **Model Builder** window, under **Results** click **Pressure, 3D (dl)**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **3D Sphere**.

4 In the **Label** text field, type `Pressure and Deformation (Kozeny-Carman Permeability)`.

Surface

1 In the **Model Builder** window, expand the **Pressure and Deformation (Kozeny-Carman Permeability)** node, then click **Surface**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type `p/p0`.

4 Click to expand the **Inherit Style** section.

Deformation 1

Right-click **Surface** and choose **Deformation**.

Pressure and Deformation (Kozeny-Carman Permeability)

1 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

2 From the **Parameter value (p0k)** list, choose **1E-4**.

3 From the **Time (s)** list, choose **21.032**.

Arrow Surface 1

1 Right-click **Pressure and Deformation (Kozeny-Carman Permeability)** and choose **Arrow Surface**.

2 In the **Settings** window for **Arrow Surface**, locate the **Expression** section.

3 In the **R-component** text field, type `solid.bndl1.farr`.

4 In the **PHI-component** text field, type `solid.bndl1.farphi`.

5 In the **Z-component** text field, type `solid.bndl1.farz`.

6 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type `400`.

7 Locate the **Coloring and Style** section. From the **Arrow base** list, choose **Head**.

8 From the **Color** list, choose **Gray**.

9 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface**.

10 Clear the **Arrow scale factor** checkbox.

11 Clear the **Color** checkbox.

12 Clear the **Color and data range** checkbox.

13 Clear the **Transparency** checkbox.

Deformation 1

Right-click **Arrow Surface 1** and choose **Deformation**.

Pressure and Deformation (Kozeny-Carman Permeability)

1 In the **Settings** window for **3D Plot Group**, click to expand the **Title** section.

2 From the **Title type** list, choose **Manual**.

3 In the **Title** text area, type `Surface: Normalized Pore Pressure, Arrow Surface: Pressure load p\[_{0}\]`.

4 In the **Parameter indicator** text field, type `p\[_{0} = 100\] Pa, t =21 s`.

5 Click the **Go to Default View** button in the **Graphics** toolbar.

6 Click the **Zoom Extents** button in the **Graphics** toolbar.