Gravity Rockfill Dam Construction and Impounding
# Outline

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1 Description

This tutorial demonstrates how the construction and impounding of a roller compacted concrete dam can be simulated with a plane strain analysis. The dam consists of 10 layers of concrete fill which are installed one-by-one and a compaction load is applied immediately after installation of each layer. The dam is resting on a soil foundation [Fig. 1]. The construction phases of the dam are assumed to be static, that means that no time effects are considered. The dam body is modeled with a Cam-clay elastoplastic material model. After the construction of the dam is finished the water level at the upstream side increases with time and the water penetrates the roller compacted concrete dam as time progresses. For this impounding stage we do a transient analysis, where we first calculate pressure heads for the different time steps and water level development in the dam body. Subsequently, we do a structural analysis for the same time steps where the water pressure in the dam and the external hydrostatic water load are applied, in which the water height corresponds to the respective time steps. The following results are calculated for this model: effective stress and pore pressure, pressure head, plastic volumetric strain, the preconsolidation pressure in the Cam-clay model, and the external hydrostatic forces, which are applied automatically by DIANAIE.

Figure 1: Dam divided in 10 layers on foundation
2 Finite Element Model

We start a new project for plane strain structural analysis with groundwater flow. We define quadratic mesh order. The model size is set to 1000 m (-500 to 500 m) to include the entire model. We choose the default units in DianaIE, except for the angles that we choose degrees instead of radians. During the material and load definition we use the default time unit seconds, but for the analysis settings definition we change to days, because this is a better reference for the reader. Results are presented in N/m² and time steps refer to days. The units and the directions are displayed in the reference system section of the geometry browser.
2.1 Geometry
First we define a quadrilateral sheet for the foundation with size 200 × 30 m in the XY plane at Z = 0 m and name it Foundation.

Main menu ➔ Geometry ➔ Create ➔ Add polygon sheet ➔ [Fig. 5]

Figure 5: Add polygon sheet

Figure 6: Foundation sheet
We define a quadrilateral face for the dam body. The dam has a base width of 100 m and a crest width of 20 m. The height of the dam is 40 m. The name of the face is *Dam*.

**Figure 7:** Add polygon sheet

**Figure 8:** Dam sheet
We want to divide the dam sheet into 10 layers and therefore define a sheet with name *Helpsheet*. This sheet is defined in the *XZ* plane at *Y* = 4 m. The *Helpsheet* is copied eight times with a distance of *Y* = 4 m.

**Main menu ➔ Geometry ➔ Create ➔ Add polygon sheet** 🛠️ [Fig. 9] [Fig. 10]

**Main menu ➔ Geometry ➔ Modify ➔ Array copy** 🏛️ [Fig. 11] [Fig. 12]
We subtract the nine Helpsheets from the Dam sheet, which result in a dam consisting of ten layers. When the dam is divided in layers we rename the layers counting from 1 at the bottom with name Dam Layer 1 to 10 at the top with name Dam Layer 10. The names before renaming are displayed in Figure 15 and after renaming in Figure 16.
2.2 Supports

We define supports in a set named $BC$ which is always active and represent the interaction of the model with the environment. The displacements at the vertical edges and the bottom edge of the foundation are supported in the directions normal to these edges.

Main menu ➔ Geometry ➔ Assign ➔ Add supports [Fig. 17] – [Fig. 20]

Figure 17: Support edges normal to $X$ direction

Figure 18: Edges selected for $BCX$

Figure 19: Edges selected for $BCY$

Figure 20: Support edges normal to $Y$ direction
2.3 Fixed Heads

We define fixed heads in a set with name *Fixed head* which is always active. DIANAIE neglects these fixed heads in the stages without groundwater conditions such as the construction of the dam. Fixed heads are defined at the upstream faces of the dam layers [Fig. 22].

**Main menu** ➔ Geometry ➔ Assign ➔ Add fixed heads ➔ [Fig. 21] [Fig. 22]

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**Figure 21:** Edit fixed heads

**Figure 22:** Selection of edges with fixed heads
2.4 External Heads

External heads are defined at the downstream face of the dam layers. For this, we first define a boundary connection to these edges. The name of the connection is *External head boundaries*. We select the ten edges at the left side (downstream) of the dam layers [Fig. 23]. For the conductivity of the resistance layer we define a value of $1 \text{ s}^{-1}$, which means a negligible resistance for the water to flow through this boundary.

**Main menu** ➔ Geometry ➔ Assign ➔ Add connection ➔ [Fig. 24] ➔ Material ➔ Add material ➔ [Fig. 25] ➔ Edit connections ➔ [Fig. 23] ➔ Edit material ➔ [Fig. 26]

Figure 23: Selection of edges with external head boundary

Figure 24: Properties external head boundary interfaces

Figure 25: Add resistance for external head boundary

Figure 26: Resistance value for external head boundary

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2.5 Loads

We first define a unit force per length at the top of each of the dam layers. When we later apply these loads we multiply the unit value with the pressure value. On this sheet we show the input for the first five dam layers and on the next sheet for the layers six to ten.

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Main menu ➔ Geometry ➔ Assign ➔ Add loads 🛠️ [Fig. 27] [Fig. 29] [Fig. 31] [Fig. 33] [Fig. 35]

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Figure 27: Edit load for layer 1

Figure 28: Selection top edge layer 1

Figure 29: Edit load for layer 2

Figure 30: Selection top edge layer 2

Figure 31: Edit load for layer 3

Figure 32: Selection top edge layer 3

Figure 33: Edit load for layer 4

Figure 34: Selection top edge layer 4

Figure 35: Edit load for layer 5

Figure 36: Selection top edge layer 5
And for the layers six to ten we do the following load definitions.

Main menu ➔ Geometry ➔ Assign ➔ Add loads 📦 [Fig. 37] [Fig. 39] [Fig. 41] [Fig. 43] [Fig. 45]
2.6 Groundwater Boundary Conditions

Now we define the initial condition for the groundwater flow analysis in the impounding phase. Therefore, we define a boundary condition set with the name *Initial*. In this set we define a head value of 0 m for the fixed heads at the upstream side of the dam and an external head value of 0 m for the boundary interface edges at the downstream side of the dam.

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**Figure 47**: Edit initial upstream fixed head

**Figure 48**: Edges for initial upstream fixed head

**Figure 49**: Edges for initial downstream external head

**Figure 50**: Edit initial downstream external head
We now define the boundary flow conditions. First, we set unit head values for a boundary condition set with name *Prescribed Heads Upstream* for the edges at the upstream side of the dam and a boundary condition set with name *External Heads Downstream* for the boundary interfaces at the downstream side of the dam.

**Figure 51:** Edit prescribed upstream fixed head  
**Figure 52:** Edges for prescribed upstream fixed head  
**Figure 53:** Edges for external downstream head  
**Figure 54:** Edit downstream external head
As last step in the boundary condition definition we define time functions for the boundary condition sets with the names *Prescribed Heads Upstream* and *External Heads Downstream*. The initial stage is followed by ten construction stages with a duration of 20 days each. From 220 days, the impounding start and we assume that from this time on the water level rises from 0 m to 35 m (5 m under the crest) in 80 days. After that time (300 days) the water level remains constant. In the same period we assume that the external head at the downstream side increases from 0 m to 1 m.

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**Geometry browser**  ➔  **Boundary conditions**  ➔  **Prescribed Heads Upstream**  ➔  **Edit time dependency**  ➔  [Fig. 55]  [Fig. 56]

**Geometry browser**  ➔  **Boundary conditions**  ➔  **External Heads Downstream**  ➔  **Edit time dependency**  ➔  [Fig. 57]  [Fig. 58]

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1Note that the time tables are defined in unit days. Therefore, time unit must be switched to day at the begin of editing these dialogues and back to seconds when the time function have been closed.
2.7 Properties

For the foundation we define a material with name *Foundation*. In the foundation we do not consider the groundwater flow and therefore we do not activate the groundwater flow aspect for this material. We chose the material class *Soil and Rock* and the material model *Mohr-Coulomb and Drucker-Prager plasticity*. The following material parameters are chosen for the *Foundation*: Young’s modulus $E = 3.0 \times 10^9$ Pa, Poisson ratio $\nu = 0.2$, density $\rho = 2500$ kg/m$^3$, porosity $n = 0$, cohesion $c = 5.0E + 4$ N/m$^2$, friction angle $\phi = 30^\circ$, dilatancy angle $\psi = 10^\circ$, tension cut-off $= 7.0E4$ N/m$^2$ and $K_0 = 0.577$. We use regular plane strain elements.
The dam material is named **RCC**. For the dam we activate the aspect groundwater flow and we deactivate the initial stress aspect. In the material class **Soil and Rock** the material model **Cam-clay** is selected. The Cam-clay model can describe the permanent compaction of the concrete grains. The following material parameters are chosen for the dam: Young’s modulus \( E = 1.0 \times 10^8 \) Pa, Poisson ratio \( \nu = 0.3 \), density \( \rho = 2000 \) kg/m\(^3\), porosity \( n = 0.6 \), friction angle \( \phi = 25^\circ \), plastic hardening parameter \( \lambda = 0.04 \), elastic hardening parameter \( \kappa = 0.01 \) and a pressure shift \( \delta p = 5.0 \times 10^4 \) N/m\(^2\). For the groundwater flow properties we define \( 1 \times 10^{-05} \) m/s for the hydraulic conductivity and \( 1.0 \times 10^{-09} \) 1/m for the elastic storativity. We use the default isotropic directional dependency for the saturated soil properties. For the hydraulic conductivity we choose to define a multilinear diagram for the pressure head and relative hydraulic conductivity; the relation is illustrated in Figure 69. For the phreatic storativity we choose a van Genuchten function with parameters 0.05 for the residual degree of saturation, 1 for the degree of saturation for positive pressure heads, 5 m for parameter \( a \) and 1 for the parameters \( n \) and \( m \). The corresponding curve is automatically generated and displayed in the van Genuchten function plot diagram, as displayed in Figure 70.
Figure 68: Groundwater flow properties for RCC

Figure 69: Relative hydraulic conductivity as function of pressure head

Figure 70: van Genuchten function for saturation as function of total head
2.8 Mesh

We define an element size of 2 m for the dam layer sheets and we choose the triangular mesher type. For the foundation sheet we define an element size of 4 m and we choose the quadrilateral mesher type.

Figure 71: Mesh properties for dam layers
Figure 72: Mesh properties for foundation
Figure 73: Select the dam layers
Figure 74: Select the foundation
We generate the finite element mesh.

Figure 75: Finite element mesh
3 Geomechanical Staged Construction Analysis

3.1 Commands

We defined a geomechanical staged construction analysis with 12 stages. We use the user selection for choosing the output items [Fig. 77]: total Green-Lagrange strains, volumetric plastic strains, effective Cauchy stresses, consolidation stresses, total heads and head pressures, pore pressures and total pressure potentials and external hydrostatic forces.

For the structural iteration method we choose the method constant stiffness [Fig. 79].

Subsequently, we define the stages one by one and each new stage is created by copying the previous one so that we only need to change the differences with respect to the previous stage.

DianaIE
We define the first stage *Initial*: there is no water level and mesh set *Foundation* is active. The support set *BC*, the fixed potential set *Fixed head* and the connection *External head boundaries* are active.

**Figure 80:** Analysis browser - stage *Initial*

**Figure 81:** Stage information *Initial*
For the next stage we copy the Initial stage and rename the new stage as Add layer 1. In this stage we define a starting time of 20 days and we activate the Dam Layer 1 shape. Further, we activate the load case Compact Layer 1 with a load factor of 1e+05 for the compaction load on the first layer.

Figure 82: Analysis browser - stage Add layer 1

Figure 83: Stage information Add layer 1 - active parts

Figure 84: Stage information Add layer 1 - loads
For the next stage we copy the *Add layer 1* stage and rename the new stage to *Add layer 2*. In this stage we define a starting time of 40 days and we activate shape *Dam Layer 2*. Further, we activate the load case *Compact Layer 2* with a load factor of $1e+05$ for the compaction load on the second layer.

![Figure 85: Analysis browser - stage Add layer 2](https://dianafea.com)

![Figure 86: Stage information Add layer 2 - active parts](https://dianafea.com)

![Figure 87: Stage information Add layer 2 - loads](https://dianafea.com)
For the next stage we copy the *Add layer 2* stage and rename the new stage to *Add layer 3*. In this stage we define a starting time of 60 days and we activate shape *Dam Layer 3*. Further, we activate the load case *Compact Layer 3* with a load factor of $1\times10^5$ for the compaction load on the third layer.
For the next stage we copy the *Add layer 3* stage and rename the new stage to *Add layer 4*. In this stage we define a starting time of 80 days and we activate shape *Dam Layer 4*. Further, we activate the load case *Compact Layer 4* with a load factor of 1e+05 for the compaction load on the fourth layer.

Figure 91: Analysis browser - stage *Add layer 4*

Figure 92: Stage information *Add layer 4* - active parts

Figure 93: Stage information *Add layer 4* - loads
For the next stage we copy the *Add layer 4* stage and rename the new stage to *Add layer 5*. In this stage we define a starting time of 100 days and we activate shape *Dam Layer 5*. Further, we activate the load case *Compact Layer 5* with a load factor of $10^5$ for the compaction load on the fifth layer.
For the next stage we copy the Add layer 5 stage and rename the new stage to Add layer 6. In this stage we define a starting time of 120 days and we activate shape Dam Layer 6. Further, we activate the load case Compact Layer 6 with a load factor of 1e+05 for the compaction load on the sixth layer.

Figure 97: Analysis browser - Add layer 6 stage

Figure 98: Stage information Add layer 6 - active parts

Figure 99: Stage information Add layer 6 - loads
For the next stage we copy the *Add layer 6* stage and rename the new stage to *Add layer 7*. In this stage we define a starting time of 140 days and we activate shape *Dam Layer 7*. Further, we activate the load case *Compact Layer 7* with a load factor of $1.0 \times 10^5$ for the compaction load on the seventh layer.

Figure 100: Analysis browser - *Add layer 7* stage

Figure 101: Stage information *Add layer 7* - active parts

Figure 102: Stage information *Add layer 7* - loads
For the next stage we copy the *Add layer 7* stage and rename the new stage to *Add layer 8*. In this stage we define a starting time of 160 days and we activate shape *Dam Layer 8*. Further, we activate the load case *Compact Layer 8* with a load factor of $1.0 \times 10^5$ for the compaction load on the eighth layer.

Figure 103: Analysis browser - *Add layer 8* stage

Figure 104: Stage information *Add layer 8* - active parts

Figure 105: Stage information *Add layer 8* - loads
For the next stage we copy the *Add layer 8* stage and rename the new stage to *Add layer 9*. In this stage we define a starting time of 180 days and we activate shape *Dam Layer 9*. Further, we activate the load case *Compact Layer 9* with a load factor of 1.0e+05 for the compaction load on the ninth layer.

Figure 106: Analysis browser - *Add layer 9* stage

Figure 107: Stage information *Add layer 9* - active parts

Figure 108: Stage information *Add layer 9* - loads
For the next stage we copy the *Add layer 9* stage and rename the new stage to *Add layer 10*. In this stage we define a starting time of 200 days and we activate shape *Dam Layer 10*. Further, we activate the load case *Compact Layer 10* with a load factor of 1.0e+05 for the compaction load on the tenth layer.

Figure 109: Analysis browser - *Add layer 10* stage

Figure 110: Stage information *Add layer 10* - active parts

Figure 111: Stage information *Add layer 10* - loads
The last stage is Impounding. Also for this stage we copy the Add layer 10 stage and rename the new stage to Impounding. In this stage we define a starting time of 220 days and choose the type Computed transient. This means that the pore pressure can be calculated in time steps. We define 10 time steps of 20 days each. We choose the boundary case Initial as initial state for the groundwater flow analysis. All model parts are already active. There are no load cases active in this stage. After the last stage is defined, we run the analysis.

**Main menu ➔ Analysis ➔ Run selected analysis**

**Figure 112: Analysis browser - Impounding stage**

**Figure 113: Stage information Impounding**
3.2 Results

To see the results we switch off the option of showing the deformed mesh. For an easier comparison, for all the presented results, we use a common color scale for the different steps: we set the properties of the contour or vector plots (specified option) with the extreme values of the presented results as minimum and maximum limits. First, we check the effective vertical stresses in three stages during construction and at three time steps during impounding. We choose the result steps: Add Layer 3, Time 60 day, Add Layer 7, Time 140 day, Add Layer 10, Time 200 day, Impounding, Time 260 day, Impounding, Time 300 day and Impounding, Time 1 year 55 day.
We show contour plots of the volumetric plastic strain in the initial stage, in three stages during construction and at two time steps during impounding. We choose the result steps: *Initial, Time 0.0000 s, Add Layer 3, Time 60 day, Add Layer 7, Time 140 day, Add Layer 10, Time 200 day, Impounding, Time 260 day* and *Impounding, Time 300 day*. We can observe that the maximum compressive strain occurs at the top of the new layers.

**Results browser → RCCDam → Output → Element results → Plastic Strains → Epvol**

**Fig. 120** – **Fig. 125**

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**Figure 120**: Volumetric plastic strains after 0 days

**Figure 121**: Volumetric plastic strains after 200 days

**Figure 122**: Volumetric plastic strains after 60 days

**Figure 123**: Volumetric plastic strains after 260 days

**Figure 124**: Volumetric plastic strains after 140 days

**Figure 125**: Volumetric plastic strains after 300 days
We show the consolidation stresses in the initial stage, in three stages during construction and at two time steps during impounding. We choose the result steps: Initial, Time 0.0000 s, Add Layer 3, Time 60 day, Add Layer 7, Time 140 day, Add Layer 10, Time 200 day, Impounding, Time 260 day and Impounding, Time 300 day.

Results browser ➔ RCCDam ➔ Output ➔ Element results ➔ Consolidation Stress ➔ Pc  [Fig. 126] – [Fig. 131]
We check the pore pressure contours in six time steps during impounding. We choose the result steps: **Impounding, Time 220 day**, **Impounding, Time 260 day**, **Impounding, Time 280 day**, **Impounding, Time 320 day**, **Impounding, Time 360 day** and **Impounding, Time 1 year 55 day**. We set the properties of the contour plot (specified option) with lower limit of 0 and upper limit of 1 N/m². We define a brownish color for the lower end of the color scale and a blueish color for the upper end of the color scale. This illustrates nicely the development of the water front in the dam body in time, during the impounding stage.

**Results browser** ➔ **RCCdam** ➔ **Output** ➔ **Element results** ➔ **Pore pressure** ➔ **PR**  [Fig. 132] - [Fig. 137]

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**Figure 132**: Pore pressures after 220 days

**Figure 133**: Pore pressures after 320 days

**Figure 134**: Pore pressures after 260 days

**Figure 135**: Pore pressures after 360 days

**Figure 136**: Pore pressures after 280 days

**Figure 137**: Pore pressures after 420 days
We show the pressure head contours in six time steps during impounding. We choose the result steps: **Impounding, Time 220 day**, **Impounding, Time 260 day**, **Impounding, Time 280 day**, **Impounding, Time 320 day**, **Impounding, Time 360 day** and **Impounding, Time 1 year 55 day**. We change back to the default settings for contour color scale colors.

**Figure 138**: Pressure heads after 220 days

**Figure 139**: Pressure heads after 320 days

**Figure 140**: Pressure heads after 260 days

**Figure 141**: Pressure heads after 360 days

**Figure 142**: Pressure heads after 280 days

**Figure 143**: Pressure heads after 420 days
Finally we display the vectors of the external hydraulic forces in six time steps during impounding. When the water head is defined DIANAIE automatically calculates this loading for the structural analysis from the input for the pressure head. We choose the result steps: Impounding, Time 220 day, Impounding, Time 260 day, Impounding, Time 280 day, Impounding, Time 320 day, Impounding, Time 360 day and Impounding, Time 1 year 55 day.

Results browser → RCCDam → Output → Nodal results → External Hydrostatic Forces → FEhydXYZ → DIANAIE

RCCDam Output Nodal results External Hydrostatic Forces FEhydXYZ

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Figure 144: External hydrostatic forces after 220 days
Figure 145: External hydrostatic forces after 260 days
Figure 146: External hydrostatic forces after 280 days
Figure 147: External hydrostatic forces after 320 days
Figure 148: External hydrostatic forces after 360 days
Figure 149: External hydrostatic forces after 420 days
Appendix A  Additional Information

Folder: Tutorials/GravityRockfillDam

Number of elements \( \approx 1900 \)

Keywords:
- ANALYS: flowst nonlin phase physic stagco stagge.
- CONSTR: head suppor.
- ELEMEN: b2gw cqlbe ct12e flow ground pstrai t3gw.
- LOAD: buoyan edge elemen force head node pressu time weight.
- MATERI: clay consta crack cutoff eggcam elasti full harden hydcnd isotor mohrco multil permea plasti porosi retent smear soften soil strain.
- OPTION: adapti consta direct loadin nonsym size units.
- POST: binary ndiana.
- PRE: dianai.
- RESULT: cauchy effect extern force green head plasti pressu strain stress total.
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