Chapter 5
3D Dam Stability

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3D Dam Stability

Section 1
Overview

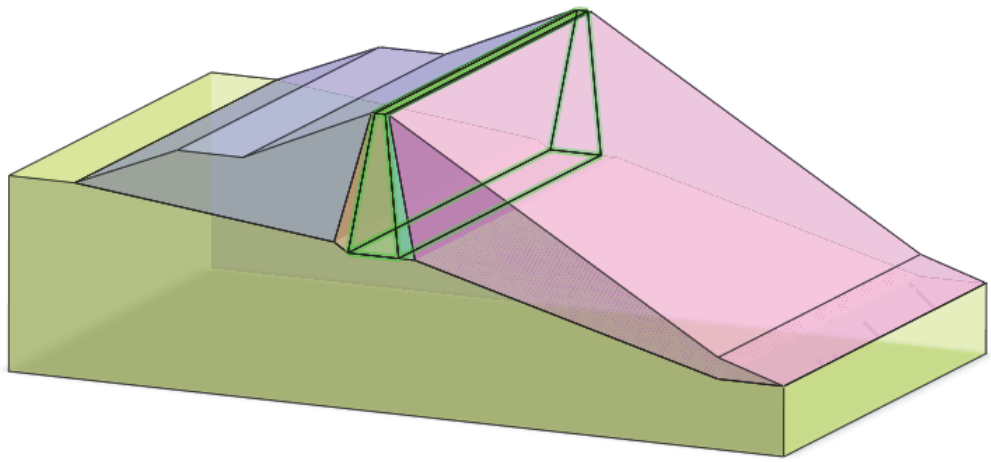
1.1 Learning Purpose

In this tutorial dam stability is verified under full water level and sudden drawdown conditions through 3D seepage analysis. Seepage analysis can be divided into 'Steady state analysis' and 'Transient analysis'.

Steady state analysis assumes that the ground is saturated and therefore draws relatively larger external force. It is beneficial in the aspect of safety but not in the aspect of economical design. Transient analysis assumes that the boundaries vary according to time. Generally, the ground is in unsaturated status, and time is different for seepage to get into steady state according to moisture content and porosity. So for these cases, transient analysis needs to be performed. Especially, when the water level drops, the high pore water pressure remaining in the dam body can affect the dam's stability.

This tutorial performs both steady state analysis and transient analysis.

▶Analysis model overview



In this tutorial, the following main concepts will be explained:

- The characteristic of ground permeability/Unsaturated
- Setting seepage boundary conditions and options - Nodal head/Review
- Setting water level fluctuation function and time step
- Dam stability according to time step (water level fluctuation)

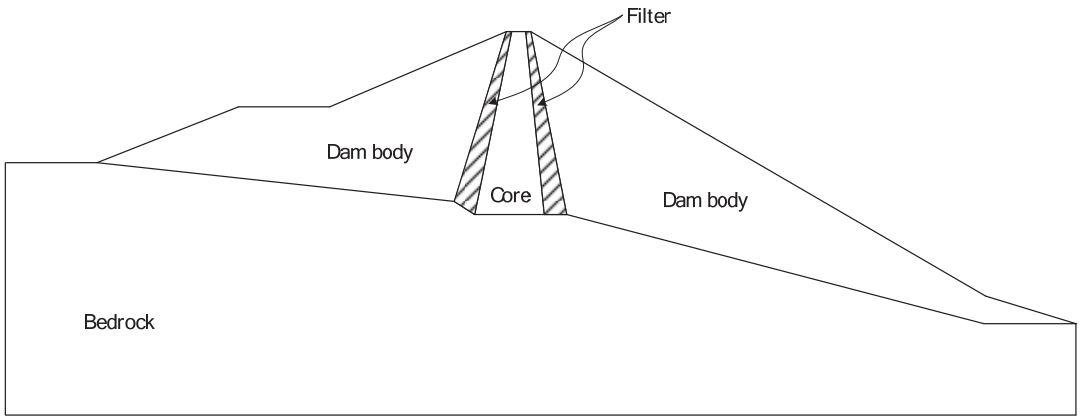
1.2 Model and Analysis Summary

The model used in this tutorial is a 3D dam of 30m height, 150m width, and 100m length on the top of bedrock.
Analysis is performed to review the dam stability in full water level and sudden drawdown conditions. To guarantee the dam stability, clay core and relatively large filter are installed in the dam body.

From the origin of GCS, simulate the condition of water level drop from 20m to 5m. Three construction stages are defined. In the first stage, assume that the ground is saturated because it has maintained full water level for a long time. Define the second stage as transient stage to analyze the change of pore pressure in dam body during water level decrease. In the final stage maintain water level (5m), and verify pore pressure inside the dam body according to time interval.

Strata configuration and model area are illustrated below.

▶Cross-section diagram



Section 2

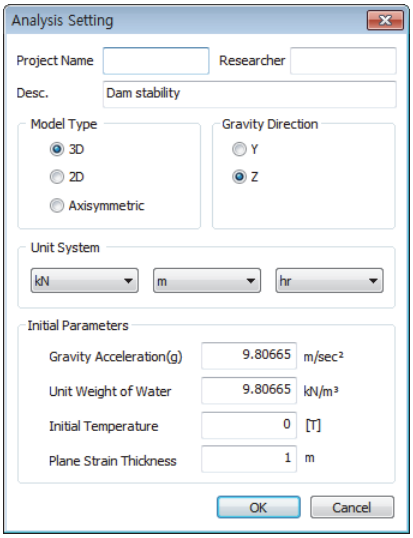
Analysis Setting

[Open the attached start file (05_Dam_start)]

* : Analysis > Analysis Case > General

Set Model type, Gravity direction and Initial parameters. Check the Unit system which will apply to the analysis. The unit system can be changed both during the modeling process and after performing analysis. The input parameters will automatically converted to the right unit system.

The model used in this tutorial is 3D model with Z gravity direction. The model uses SI unit system (kN, m) and time unit of 'hr' to define permeability.



Section 3
Define Material and Property

Define ground materials and properties, and assign them to mesh sets during mesh generation.

3.1 Define Ground Material (Define Unsaturated Characteristic)

For material model type, use "general Mohr-coulomb" for this tutorial. Material for each stratum is shown in the following table. For unsaturated characteristic apply experimental value. (Items of porous material in the table are applied to seepage analysis.)

▶Table. Ground material

Name	Core	Filter	Dam body	Bedrock
Material	Isotropic	Isotropic	Isotropic	Isotropic
Model Type	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb
General				
Elastic Modulus(E)	4.0E+04	5.0E+04	5.2E+04	2.0E+06
Poisson's Ratio(v)	0.35	0.33	0.3	0.2
Unit Weight(r)	20	20	19	23
Ko	0.5	0.5	0.74	0.6
Porous				
Unit Weight(Saturated)	21	22	22	23
Initial Void Ratio(eo)	0.5	0.5	0.5	0.5
Unsaturated	Core	Filter	Dam body	-
Kx	1.92E-05	1.00E-04	0.01	1.00E-05
Ky	1.92E-05	1.00E-04	0.01	1.00E-05
Kz	1.92E-05	1.00E-04	0.01	1.00E-05
Specific Storability(Ss)	Auto	Auto	Auto	Auto
Non-Linear				
Cohesion	30	0	0	100
Frictional Angle	35.6	33	39	43

Tip

When you process a seepage analysis by applying unsaturated characteristic of a ground, use 'Specific Storability' to define a slope of volumetric water content in saturated condition. 'Specific Storability' is a coefficient which describes properties of compressive fluid. This signifies outflow or inflow volume through unit volume of aquifer during increase or decrease of water level. You can input it directly. Or in case of setting drainage parameters to 'Undrained', this value can be automatically calculated using 'Undrained Poisson's ratio', 'effective elastic modulus' and 'Poisson's ratio' inputted as general parameters. To prevent numeral error, it is recommended to set nonlinear Poisson's ratio to 0.5 which is close to 0.495, and use calculated value considered ground elastic modulus and Poisson's ratio.

$$K_f = BK_u = \frac{E'(\nu_u - \nu')}{(1-2\nu')(1+\nu')(1-2\nu_u)}$$

$$S_s = \frac{n\gamma_w}{K_w} = \frac{\gamma_w}{K_f}$$

$$S_s = \gamma_w \frac{(1-2\nu')(1+\nu')(1-2\nu_u)}{E'(\nu_u - \nu')}$$

For the further information refer to the 'User Manual Ch.4 (Material Property)'.

3.2 Define Property

Properties represent physical attributes of the meshes and will be assigned to mesh sets during mesh generation. While defining ground and structure properties, you should choose the material to be used. Refer to the following table for each structure's material.

▶Table. Ground property

Name	Core	Filter	Dam body	Bedrock
Type	3D	3D	3D	3D
Material	Core	Filter	Dam body	Bedrock

3.3 Define function

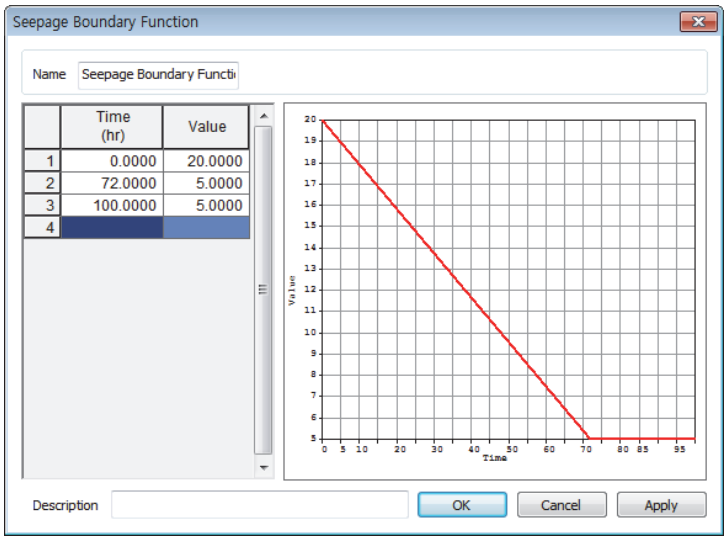
∗ : **Seepage/Consolidation Analysis > Prop./CSys./Func. > Function > Seepage Boundary**

This process defines function of seepage boundary according to time.

Create a function which simulates the process in which the water level decreases from 20m to 5 m in 3 days (m/day).

- Select [Seepage Boundary].
- Create function by inputting (0,20),(75,5),(100,5) as following image.

▶Generate seepage boundary function



Tip

Time steps are set up to verify results of transient analysis. In case of setting steps which get out of the time range of seepage load function, automatically linear-interpolates the value of the time step from the slope of the function.
(ex) Apply uniformly 5(m) to water head value because the graph slope is '0' after 200(hr).

Section 4
Modeling

[Start modeling]

This tutorial focus on 3D geometry and elements generation, unsaturated characteristics and boundaries which are important in transient seepage analysis and analysis results output according to water level fluctuation.

Start the tutorial by opening the start file in which basic materials, properties and lines for generating 3D geometry shapes have already been predefined.

4.1 Modeling Geometry

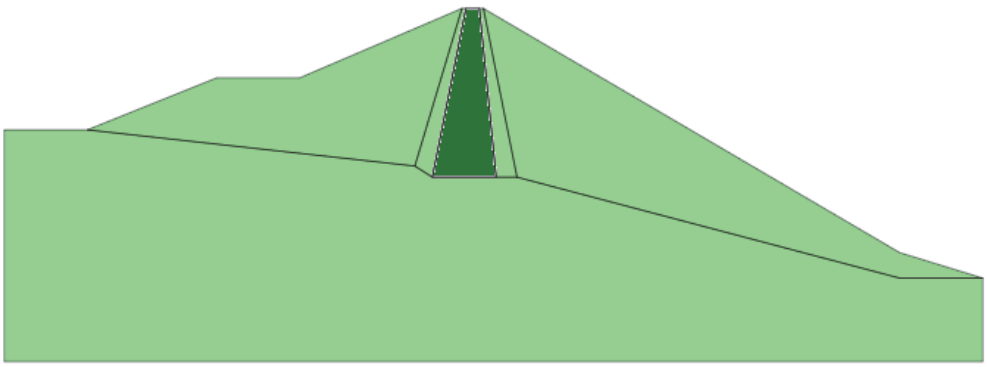
∗ : Geometry > Surface & Solid > Make Face

This process generates faces with lines or coordinates.

Generate face of each area, and extrude the faces to make solids. Make a face for dam core area.

- Select [Face] tab.
- Select lines(4) which consisting 'Core' area. The selected lines must be closed to create face.
- Click [OK].

▶Create face



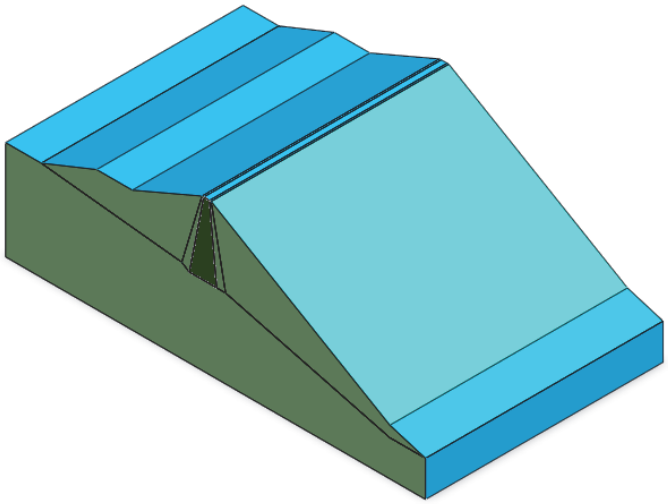
∗ : Geometry > Protrude > Extrude

This process creates line/face/solid shapes from lower shapes such as point/edge/face. With lines which constitute a closed domain, it is also possible to make a solid at once. Create 3D ground and excavation area.

Use the generated face to create all the solids at once.

- Select entire faces (6).
- Set the direction to y axis and input length to '100(m)'.
- Click [OK] and check the generated solids on the screen.

▶Generate solid



* : Geometry > Surface & Solid > Auto Connect

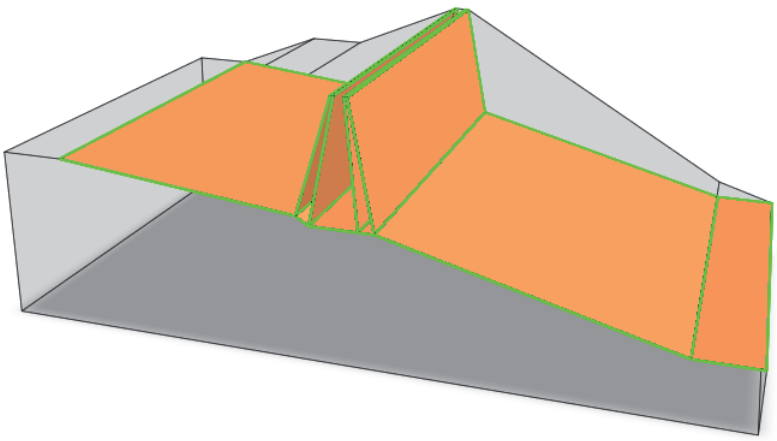
This process generates shared faces automatically after generating 3D solids. Before mesh generation, the share faces need to be created to connect nodes.

- Select all the solids (6).
- Click [OK].

Tip

To prevent the analysis error occurring from unconnected nodes between elements, it is recommended to verify the generated shared faces. Shared faces can be checked by Geometry > Tools > Check Shape > Check Geometry > Check Duplicates.

▶Auto connect



4.2 Mesh Generation

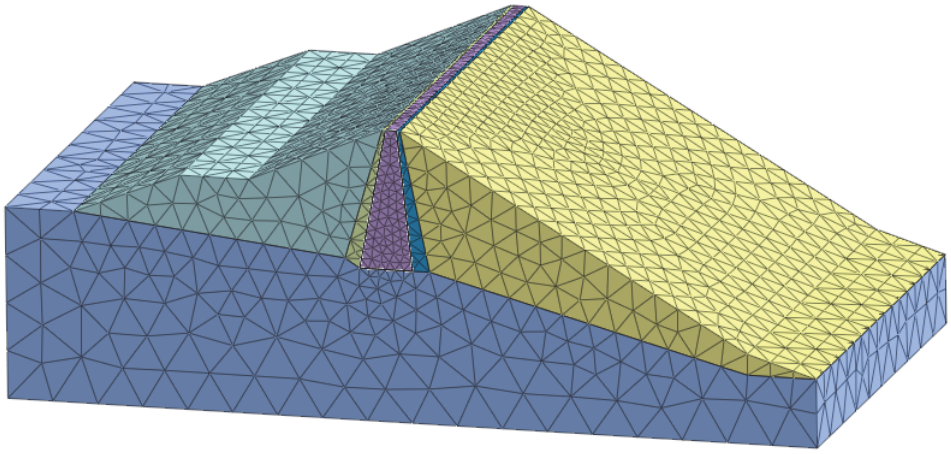
Mesh shape and mesh quality are very important in finite element analysis. Generally speaking, small mesh size makes good mesh shape (quality). However small mesh sizes will also extend analysis time. So it is recommended to determine the mesh size by considering both accuracy and efficiency of the analysis. Take this analysis as an example. Core part in dam body is the main part of this analysis, so small and dense meshes in this area are needed for more accurate analysis results. For the mesh sizes in the rest of the area, outside of the dam body and bottom part of the bedrock, mesh sizes can be set larger to save analysis time.

∗ : Mesh > Generate > 3D

This is a process of generating element for ground area. When you generate mesh of each solid you can assign its property. Refer to the model cross-section diagram generate each solid by selecting on by one.

- Select [Auto-Solid] tab.
- Select 'Core' solid.
- Input'2 for element size, and select 'Core' property.
- Click [Apply] and check the generated meshes on the screen.
- In the same way, generate mesh sets for 'filter', 'Dam body' and 'Bedrock' by inputting mesh size as 4,6,10 respectively. Choose the right properties when you generate meshes.

▶Generate mesh



Tip

After automatically generating entire element to one property, you can simply change property of each mesh set at 'change parameter'. Assign property for element by Mesh > Element > Parameter.

Section 5
Analysis Setting

5.1 Setting Boundary Condition

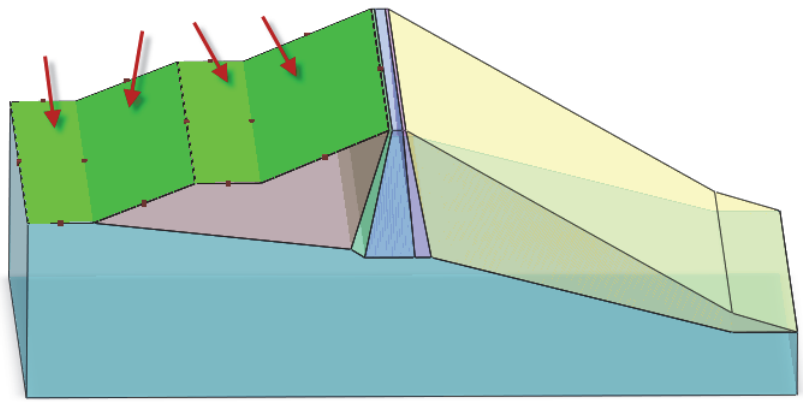
∗ : Seepage/Consolidation Analysis > Boundary > Nodal Head

This process sets water level position (Height) in the model by total head or pressure head.

Simulating the condition in which water level decreases from 20(m) to 5(m) in three days based on origin of GCS. Generate 20(m) nodal head boundary of full water level for steady state analysis, and apply seepage load function for transient analysis of the sudden draw down.

- Select 'Face' type.
- Select surfaces (4) of the left dam body as shown in the image below.
- Input full water level '20(m)' in the [Value], and select type to 'Total'.
- Check [if Total Head < Potential Head, then Q=0].
- Name the Boundary Set name to 'Steady state'. Click [Apply].
- Generate 'Transient' nodal head boundary.
- Select faces(4) same as steady state boundary.
- Input '1(m)' in value. Check [Function] and select 'Seepage boundary function' which is already generated in advance.
- Name the Boundary Set name to 'Transient' and click [OK].

▶Generating nodal head



Tip

Nodal head can be defined by total head or pressure head. If you generate elements in seepage analysis, nodes of each element automatically get potential head according to the nodal height based on GCS (0,0,0). Since 'Total head = Potential head + Pressure head' Nodal head boundary can be easily defined by pressure=0, if there is a water level at selected node(face).

Tip

[if Total Head < Potential Head, then Q=0] ; if the potential head automatically assigned to the element node is bigger than inputted total head, the nodal head boundary is deleted. When sudden draw down happens, the water head in the dam body will sustained higher water head than water level decrease during the certain time. And the water head decreased slowly as time goes by. And this option is to simulate the flow inside of the dam body.
To see the result difference depending on this option, refer to the 'Section 6. Results'.

* : Seepage/Consolidation Analysis > Boundary > Review

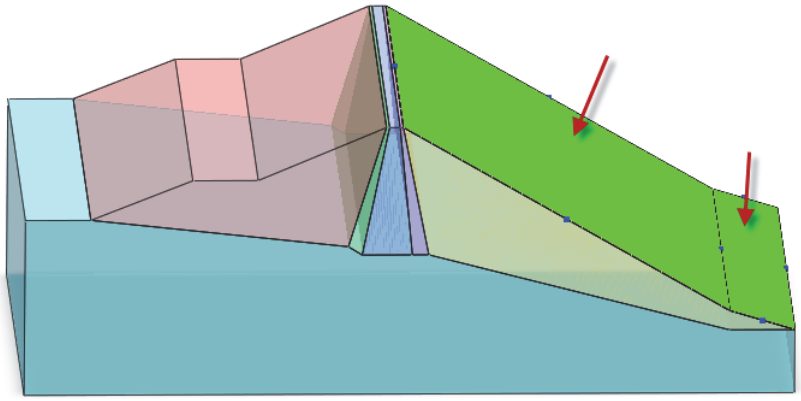
This is a boundary which detects location of water flow inside the dam body and seepage surface. When location of water level (head) is uncertain in the seepage analysis, you can set [Review].
In the node where review boundary is set,

1) If calculated pore pressure is smaller than 0, automatically deletes boundary condition at the node,
2) If calculated pore pressure is bigger than 0, automatically sets pore pressure to 0.

Through this repetitive calculation, the first location where the pore pressure is bigger than or equal to 0 is detected. And the location signifies the seepage surface.

- Set the object type to 'Face'. Select right surfaces (2) of the dam body as shown below.
- Name boundary set as 'Review'. Click [OK].

▶Generate review boundary



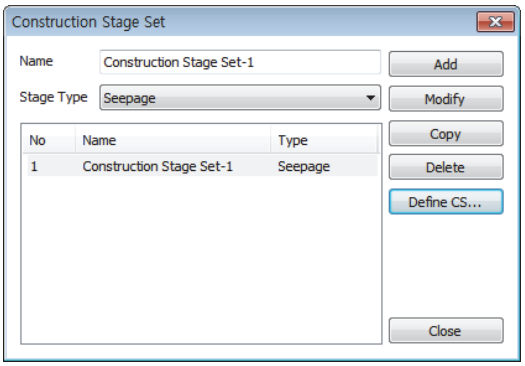
5.2 Define Construction Stages

∗ : Seepage/Consolidation Analysis > Construction Stage > Stage Set

This process sets construction stages. By defining 3 stages, verify the change of pore pressure in the dam body during full water level, sudden water drawdown, and after the sudden drawdown.
In the transient analysis stage, it is possible to set time steps and verify results of each time step.
When setting interval for time steps, seepage load function should be considered.
Once a condition is activated it will maintain until it gets deactivated. So, be sure not to overlap the data with former stage when setting Activated/Deactivated Data for analysis.

- Set stage type to [Seepage] and select [Add].
- Select the added construction stage set. And click [Define Construction Stage] button.
- Define the construction stages following the instructions below

▶Setting construction stage set



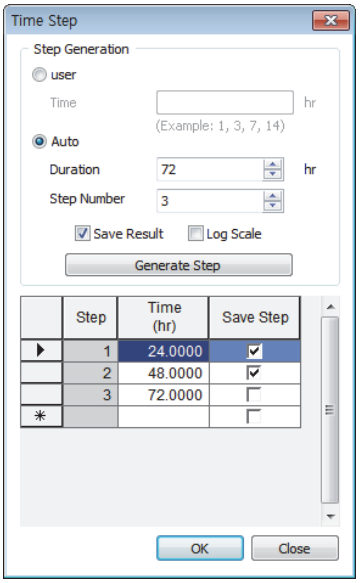
Stage 1 - Name : Full water level

- Stage Type : Steady-State
- Activated Data-Mesh : All mesh sets
- Activated Data-Boundary Condition : [Steady flow], [Review]
- Click [Save] and click [New] button.

Stage 2 - Name : Water level drawdown

- Stage Type : Transient
- Time Step : Use [Auto] generation and set 72hr in 3 steps
- Deactivated Data-Boundary Condition : [Steady flow]
- Activated Data-Boundary Condition : [Unsteady flow]
- Click [Save] and click [New] button.

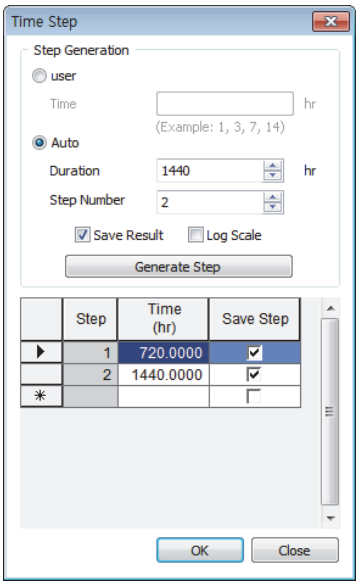
▶Transient – Setting time step



Stage 3 - Name : Maintain water level (2 month later after sudden drawdown)

- Stage Type : Transient
- After selecting time step, set time interval as following image.
- Save and click [Close]

▶Transient-Setting time step



5.3 Setting Analysis Case

This process sets the model data and analysis method. You can control analysis type and output type in advanced options. In construction analysis, the data for the each stage is set. So [Analysis Case Model] is deactivated.

∗ : **Analysis > Analysis Case > General**

- Input name. And select solution type as Construction stage.
- Uncheck [Max. Negative Pore Pressure Limit] option in the Analysis Control > General tab.
- Click [OK].

Tip

[Max. Negative Pore Pressure Limit] is an option to limit negative pore pressure which is calculated theoretically and doesn't fit with real value. If you apply unsaturated characteristic in transient analysis, water content according to negative pore pressure and changes of permeability coefficient must be considered. So, random limitations are not applied to the analysis.

5.4 Perform Analysis

Perform analysis. After the analysis is done, the software automatically switches to [Post-Mode] in which you can check analysis results. To modify model and options after the analysis, you have to switch back to the [Pre-Mode].

∗ : **Analysis > Analysis > Perform**

- Perform analysis.

Tip

During the analysis, you can see the calculation process, whether the results are converged or not, warnings and errors through the [Output Window].

Section 6
Results

It is very important to verify water head, flow rate etc. according to time variation in transient seepage analysis. After the analysis, total head of the ground, pore pressure of dam body according to each construction stage and time interval can be verified through Results Tree. Total results are plotted in contour, table, and graph. The main results to be checked are listed below.

- Pore pressure in dam body at full water level (location of seepage surface)
- Pore pressure in dam body during sudden drawdown
- Change of Pore pressure (water level) in dam body according to time.

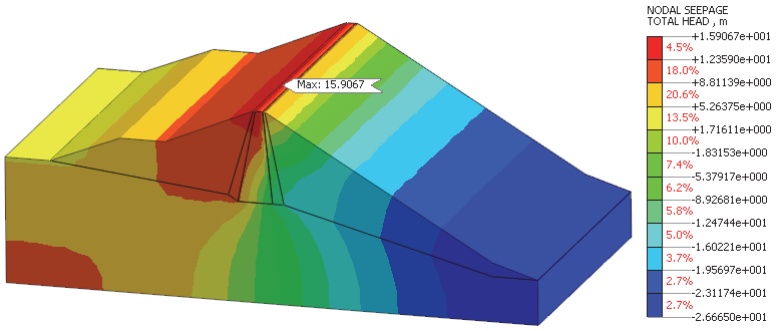
6.1 Verify Water Head

The results for water head can be verified in 'Nodal Seepage Results'. It is also possible to check total head, pore pressure, and flow rated according to changes of external water level.

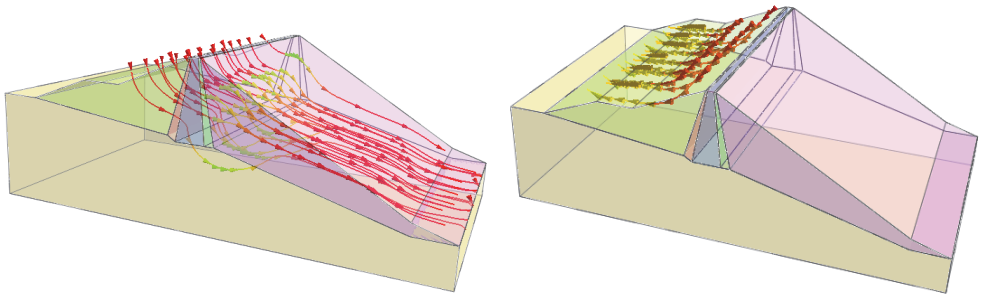
Check water head at the final stage which shows results 60 days after the water drawdown.

- Choose the final time step in the Result Tree, and select Nodal Seepage Results > TOTAL HEAD.
- Even water level dropped from 20m to 5m, you will see that the total head of the dam body maintains about 16m. This is because the descending speed of external water level is relatively faster than infiltration velocity in the ground. Therefore after the sudden drawdown, down-stream is generated at the fore-land part as shown below. Because generally very low permeability material is used for core part to assure the safety of the dam by the infiltration, the fore-land of the dam may become unstable after the sudden drawdown.

▶Total head after sudden drawdown

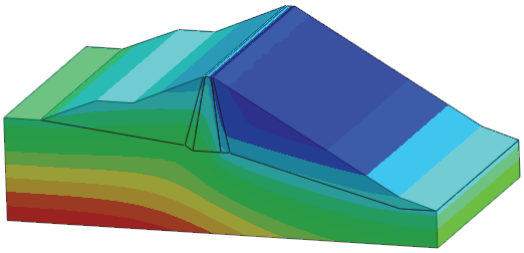


▶Steady flow of initial full water level
▶▶Flow after sudden drawdown

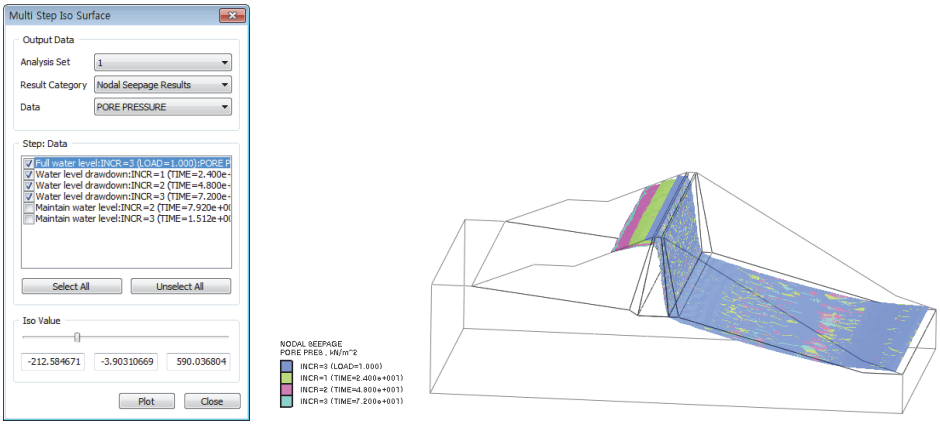


- Select the final time step in the Result Tree, and select Nodal Seepage Results > PORE PRESSURE HEAD. The face created by connecting points where the PORE PRESSURE is '0 (zero)' is a water level surface.
  This can be verified through each construction stage/time step in Result > Advance > Multi Step Iso.

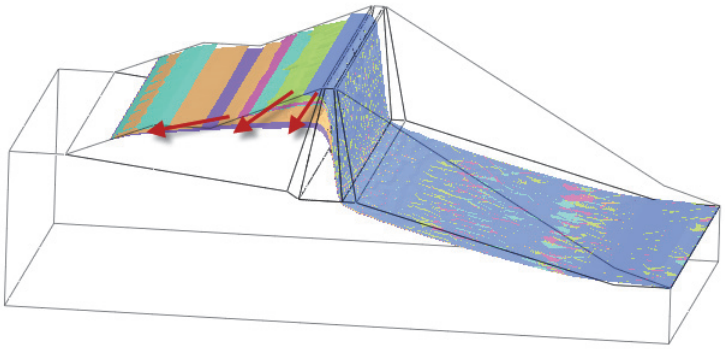
▶Pressure head after draw down



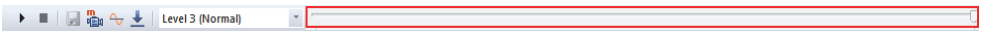
▶Muti Step iso surface(change of water level) – Right after drawdown



▶ Muti Step iso surface(change of water level) – 60 days later

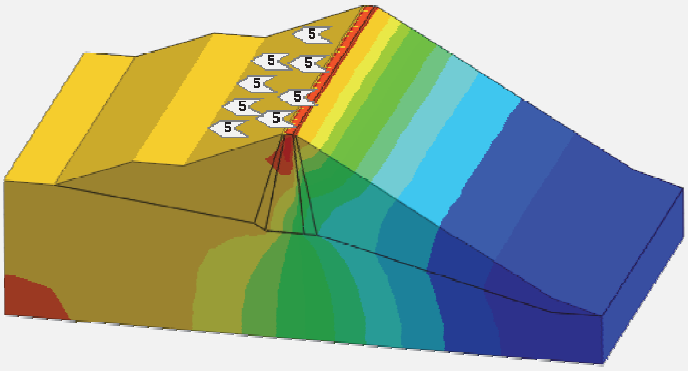


- Use the movement bar at the bottom of the screen to view the step-by-step analysis results.

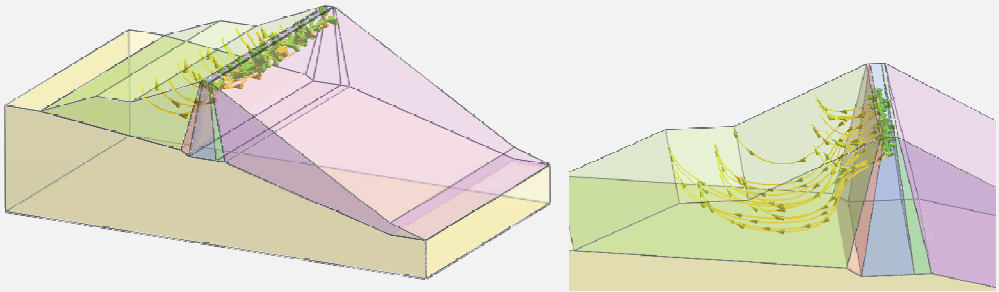


Tip

Comparing water head results of unchecked [if Total Head < Potential Head, then Q=0] option which set when defining nodal head. After the sudden drawdown from 20m to 5m, the total head of foreland simultaneously changes to 5m. The unusual reverse flow is generated from the Core which maintained high water level because of very low permeability to foreland. There is not analysis error. But you have to use the option when considering water level to prevent the unusual phenomenon which does not fit to the reality.



<Total head after sudden drawdown>



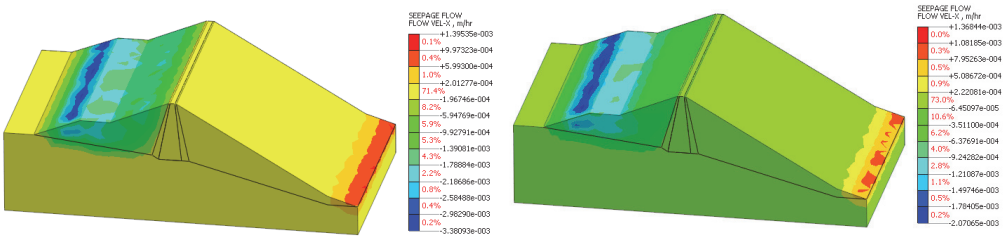
<Flow path after sudden drawdown>

6.2 Verify Element Result

Verify flow rate and hydraulic gradient to review dam stability about seepage.

- Select Final time step of Result Tree, and click 3D Element Seepage Results > FLOW VELOCITY X. (-) figure signifies inflow from foreland, and (+) figure signifies outflow from inland. Right after the sudden drawdown, outflow of foreland is maximized. As time passes by, it become similar to steady state. And then outflow increases again. Through maximum outflow velocity, it is possible to review stability about piping phenomenon etc. compare to design standard.

▶Right after sudden draw down
▶▶60 days later sudden draw down



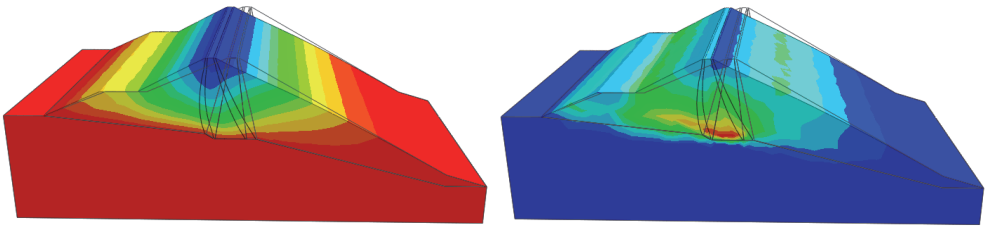
Thus, through transient analysis, you can inversely calculate the time where the ground becomes close to steady state or use as economic design material with securing stability. It is possible to review the dam stability by coupling with Seepage analysis results. You can also verify the dam deformation and the permeability change according to water level by fully coupled stress-seepage analysis.

6.3 Review Dam Stability (Coupled Analysis)

It is possible to analyze seepage results in various ways, and review stability of displacement by coupled analyzing with Stress analysis. If you add each construction stage of stress analysis in initial steady-state analysis, you can simply see the deformation degree about water level change.
For more details about construction stage and analysis control settings, refer to the '2: Construction Stage' in attached final file.

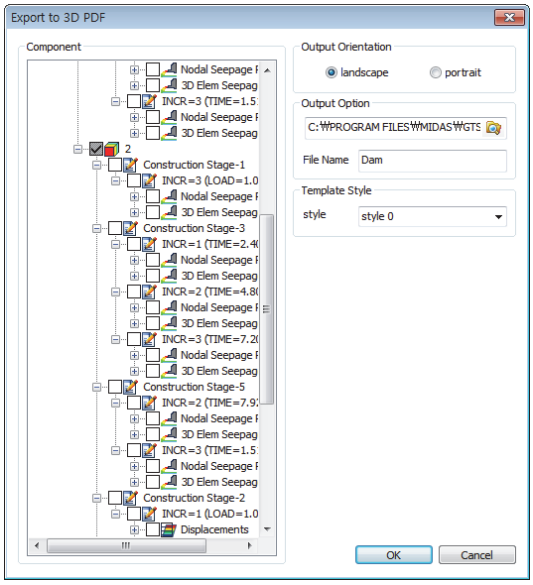
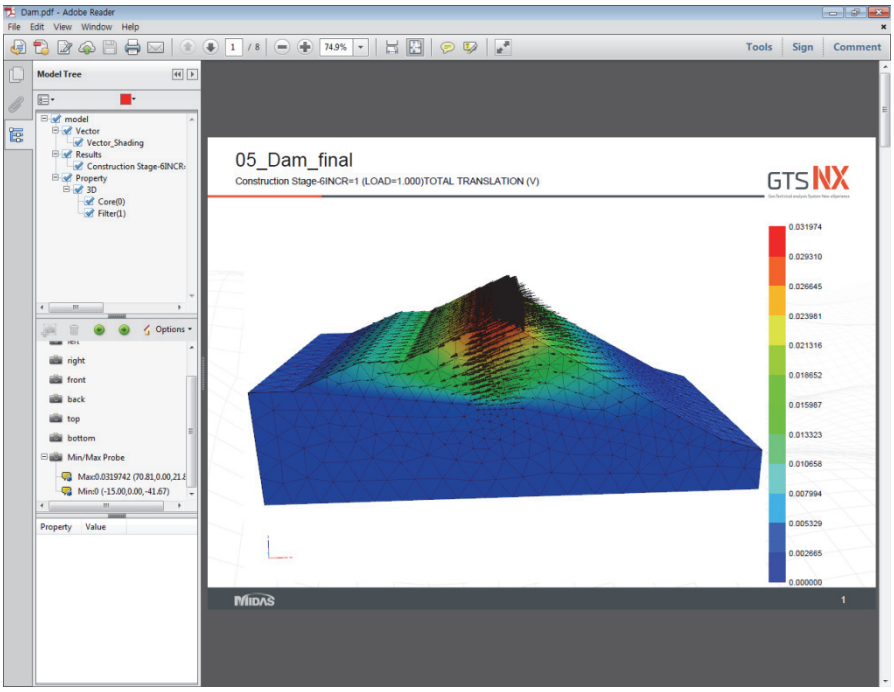
The results of Seepage-Stress Coupled analysis shows that as the sudden decrease of hydrostatic pressure occurs at surface of the force land in initial full water level, more displacement concentration occurs at the force land as time passes. The result shown below is a result of horizontal displacement and shear strain of the Dam at the final stage.

▶Horizontal displacement
▶▶Maximum shear strain



6.4 Export 3D PDF

In GTS NX, it is possible to generate pre/post model information and results in PDF Report by selecting components you want to plot. Select Tools > Export 3D PDF > Export 3D PDF, and choose the model (shape, mesh) information and result item.



In the plotted PDF file, basic motivation for checking 3D model and results is available. Also it is available for specific review such as adding dimension line and annotation, showing cutting plane, and max/min value and location. You can review from attached [Dam.pdf] file.