
Session 2.

Ensuring Earthfill Dam Safety in Seismic Zones

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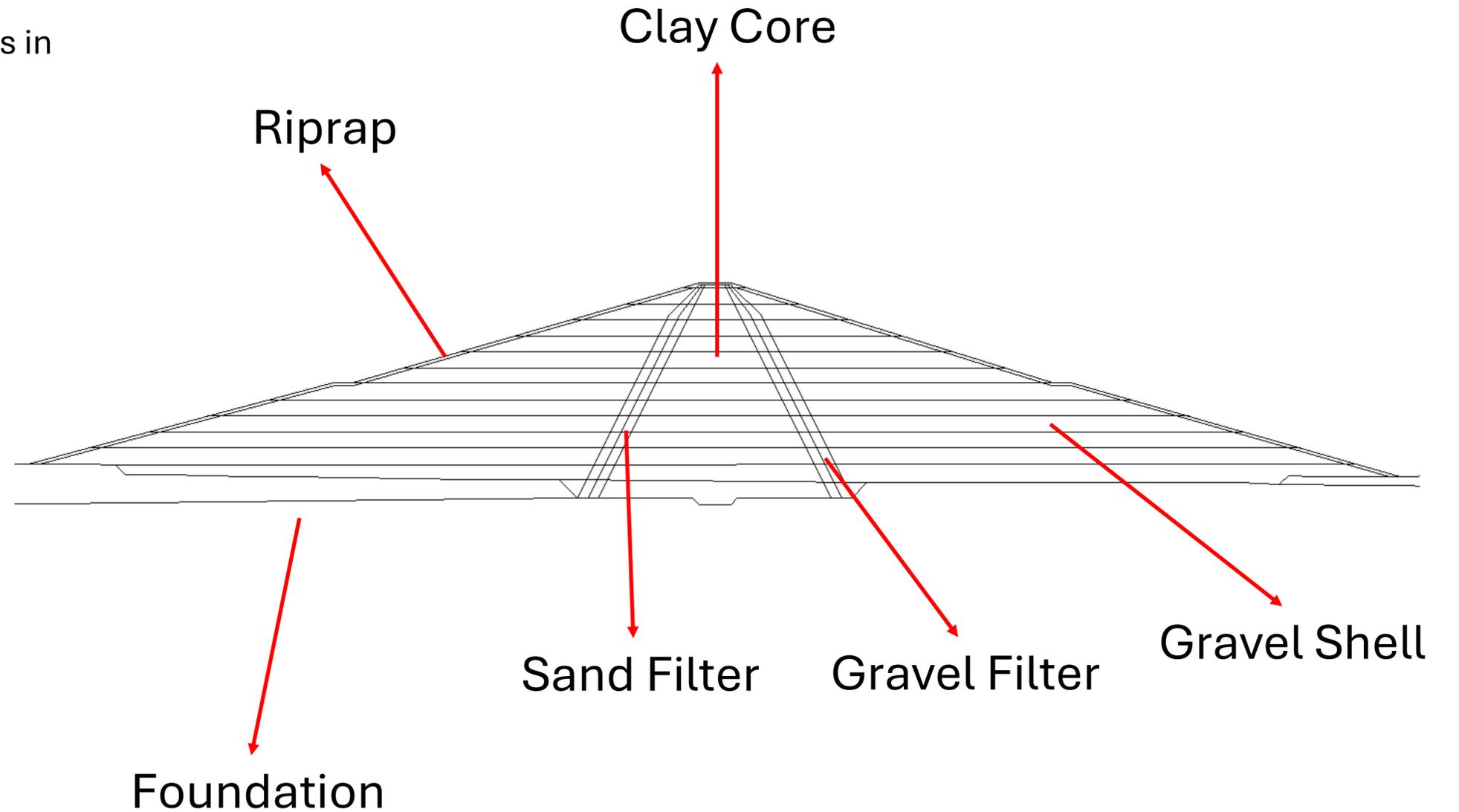
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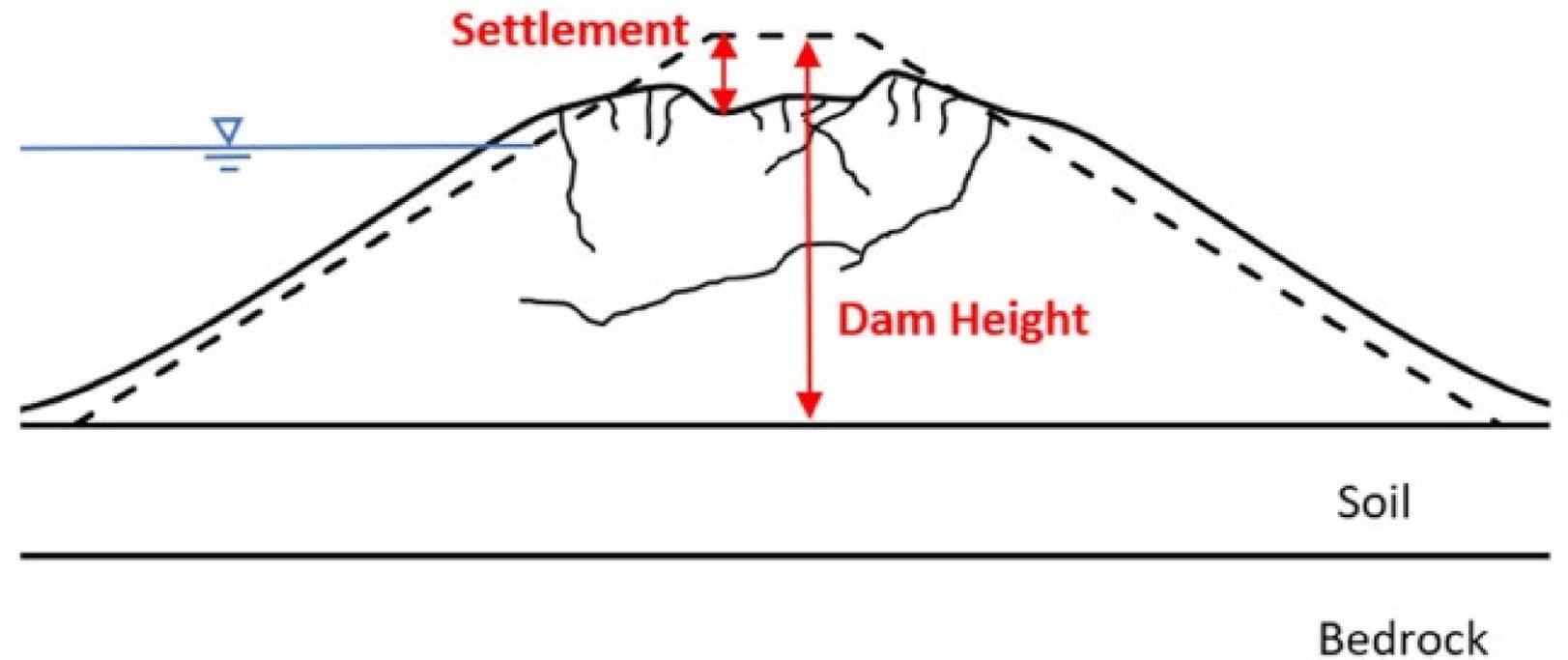
Introduction

- Embankment dam that we will analyze is 66.8 meters in height.
- Section includes:
 - Clay core
 - Sand filter
 - Gravel filter
 - Gravel shell
 - Riprap



Seismic Induced Damages

- Three types of damage may occur as a results from earthquakes:
 - Cracking
 - Sliding
 - Post-earthquake internal erosion
- Crest deformation is generally a good indicator of the damage level.
(Fell et al., 2000; Swaisgood, 1998)



He and Rahje (2024)

$$RS(\%) = \frac{\text{Crest settlement}}{\text{Dam height}} \times 100$$

Evaluation of Crest Settlement

- Evaluation of horizontal and vertical deformation mainly consists of three topics:
 - To overcome the overtopping, freeboard of the dam should be more than maximum vertical displacement (static + dynamic)
 - Maximum horizontal displacements must be lower than the thickness of the filters
 - To designate the amount of seismic induced damages, they are classified by studies in the literature
- Pells and Fell (2002)
- He and Rahje (2024)

Table 1. Capacity relationships for earth dams proposed by Pells and Fell (2002)

Damage class		Maximum longitudinal crack width (cm)	Maximum relative crest settlement (%)
Number	Description		
0	No or slight	<1	<0.03
1	Minor	1–3	0.03–0.2
2	Moderate	3–8	0.2–0.5
3	Major	8–15	0.5–1.5
4	Severe	15–50	1.5–5
5	Collapse	>50	>5

Table 2. Mean and standard deviation of the relative settlement for the capacity relationships

	$\mu_{\ln C}$	Median C (RS in %)	$\sigma_{\ln C}$
Minor	-3.507	0.03	0.94
Moderate	-0.777	0.46	0.99
Severe	0.833	2.3	0.92

He and Rahje (2024)

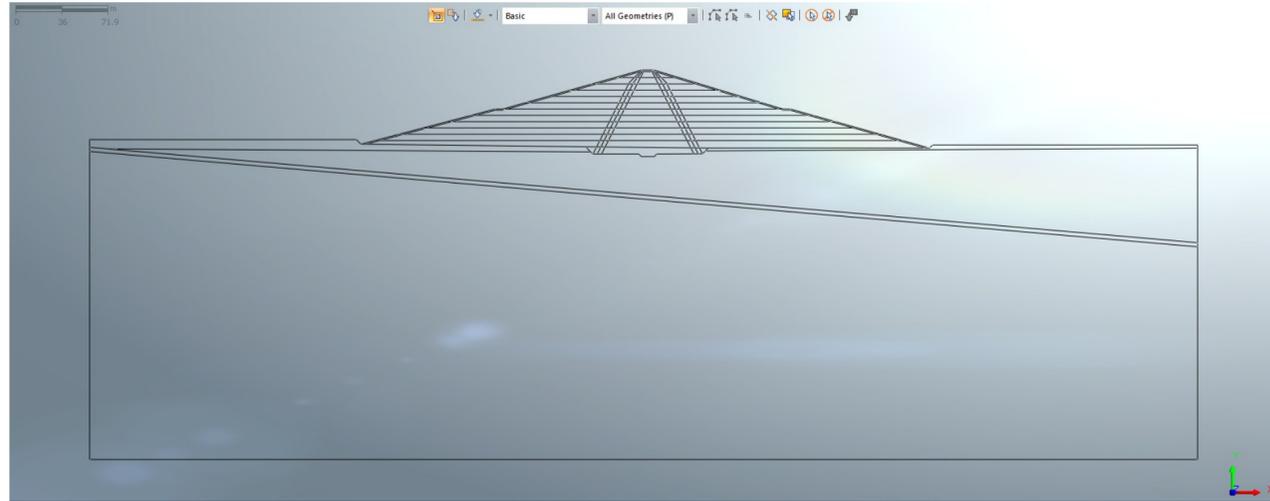
$$P_{DS}(RS) = \Phi \left[\frac{\ln(RS) - \mu_{\ln C}}{\sigma_{\ln C}} \right]$$

Material Properties

Name	E (kPa)	ν	γ (kN/m ³)	γ_{sat} (kN/m ³)	E50ref (kPa)	Eoedref (kPa)	Euref (kPa)	Failure Ratio	Ref. Pressure (Pref) (kPa)	Power of Stress Level Dependence y	Internal Friction Angle (Φ)	Dilatancy Angle (Ψ)	Cohesion (kPa)	G0ref (kPa)	Threshold Shear Strain	Permeability (m/s)
01A-ClayCore-HSS	40000	0.3	18	19	22000	22000	66000	0.9	100	0.95	18	0	40	64034.8	0.0004	3.00E-08
03A-FilterSand-HSS	45000	0.3	18	19	24750	24750	74250	0.9	100	0.6	35	3	0	134220	0.0075	0.0005
02A-FilterGravel-HSS	55000	0.3	20	21	30250	30250	90750	0.9	100	0.5	40	8	0	134220	0.0075	0.005
04A-GravelShell-HSS	60000	0.3	22	23	33000	33000	99000	0.9	100	0.5	35	8	20	134220	0.0075	0.005
05A-RipRap-HSS	65000	0.3	24	25	35750	35750	107250	0.9	100	0.5	45	13	0	134220	0.0075	0.1
06A-RiverAlluviums-HSS	55000	0.3	20	21	30250	30250	90750	0.9	100	0.5	44	12	0	134220	0.0075	0.01
01A-ClayCore-HSS(Saturated)	40000	0.3	18	19	22000	22000	66000	0.9	100	0.95	18	0	10	64034.8	0.0004	3.00E-08
03A-FilterSand-HSS(Saturated)	45000	0.3	18	19	24750	24750	74250	0.9	100	0.6	35	0	0	134220	0.0075	0.0005
02A-FilterGravel-HSS(Saturated)	55000	0.3	20	21	30250	30250	90750	0.9	100	0.5	40	8	0	134220	0.0075	0.005
04A-GravelShell-HSS(Saturated)	60000	0.3	22	23	33000	33000	99000	0.9	100	0.5	35	3	5	134220	0.0075	0.005
05A-RipRap-HSS(Saturated)	60000	0.3	24	25	33000	33000	99000	0.9	100	0.5	45	13	0	134220	0.0075	0.1
06A-RiverAlluviums-HSS(Saturated)	50000	0.3	20	21	27500	27500	82500	0.9	100	0.5	44	12	0	134220	0.0075	0.005

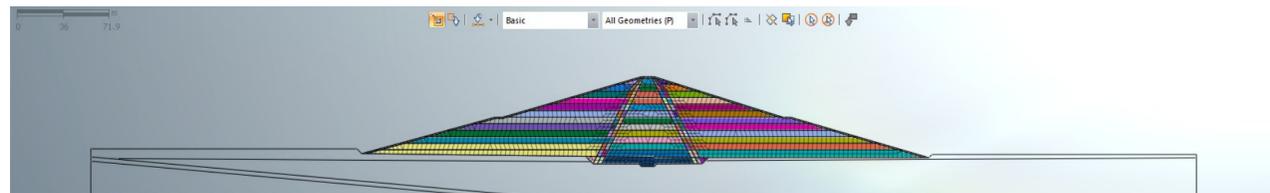
Modeling an Earthfill Dam with Construction Stages

1



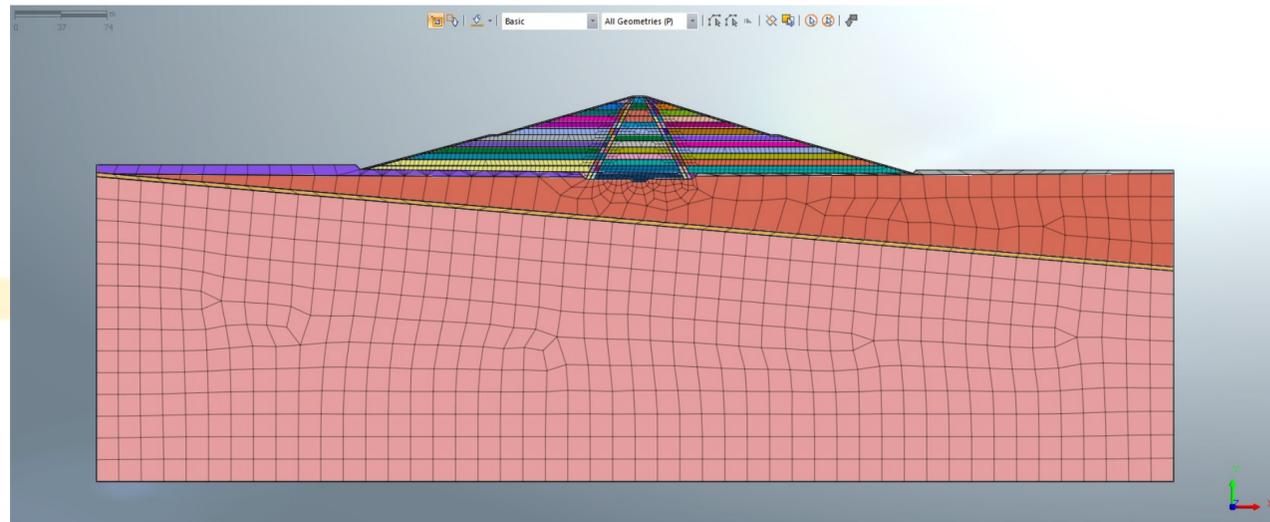
1) Importing a cross-section from .dxf file

2



2) **Fine** meshing the **dam body** with maximum of 3.5 mesh size

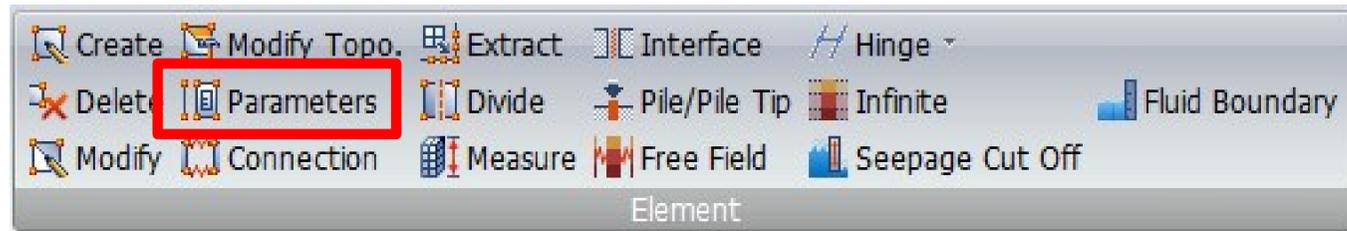
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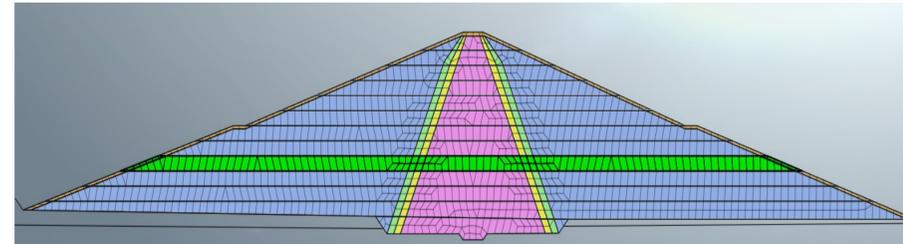
3) **Coarse** meshing the **foundation** with maximum of 18 mesh size

Useful Tools for Modeling

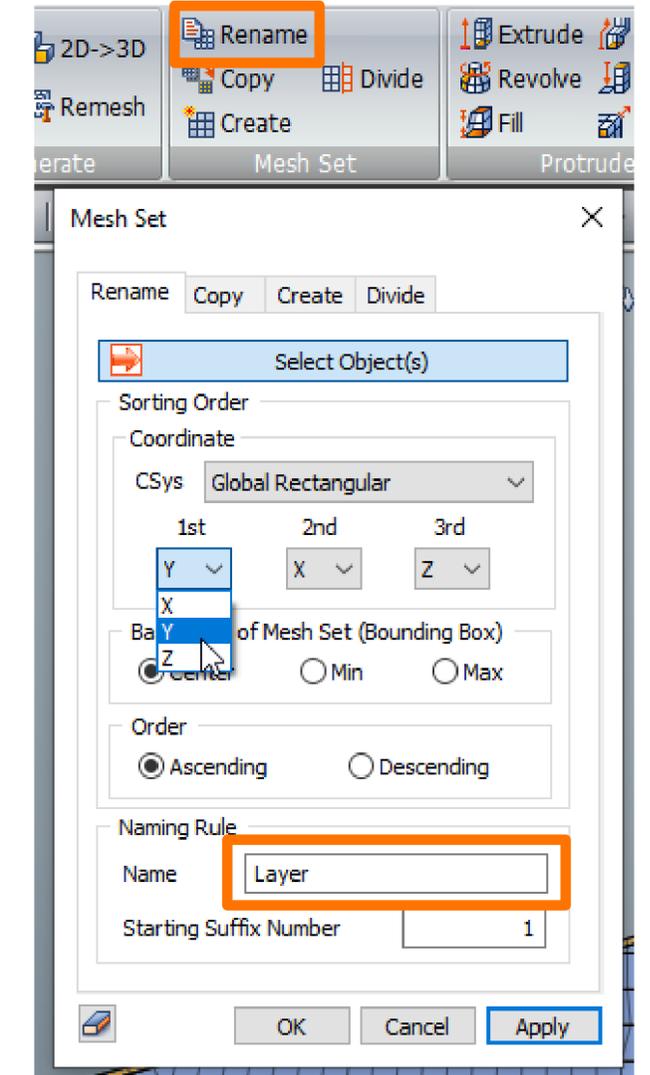
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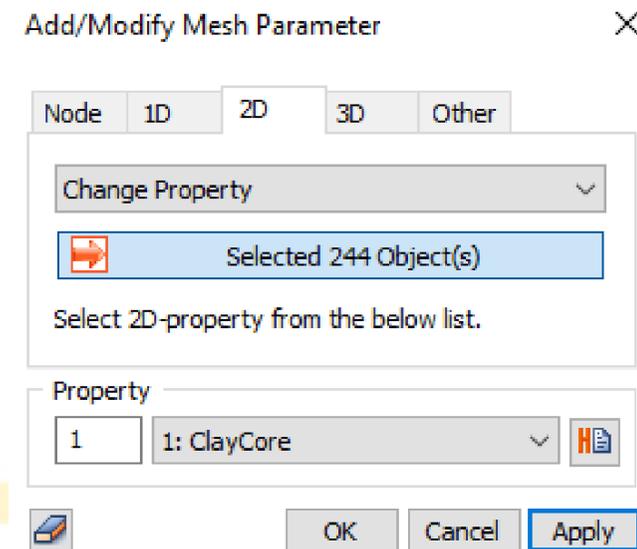
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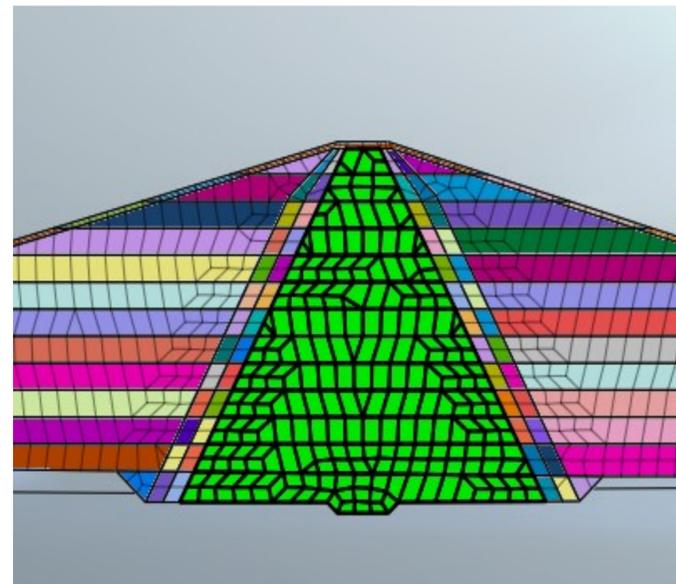
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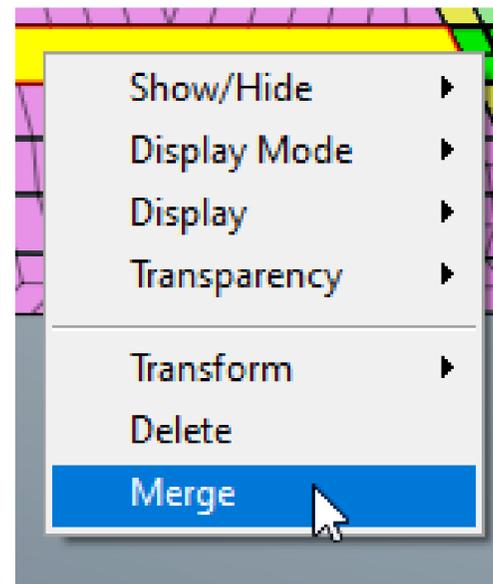
5



6



8



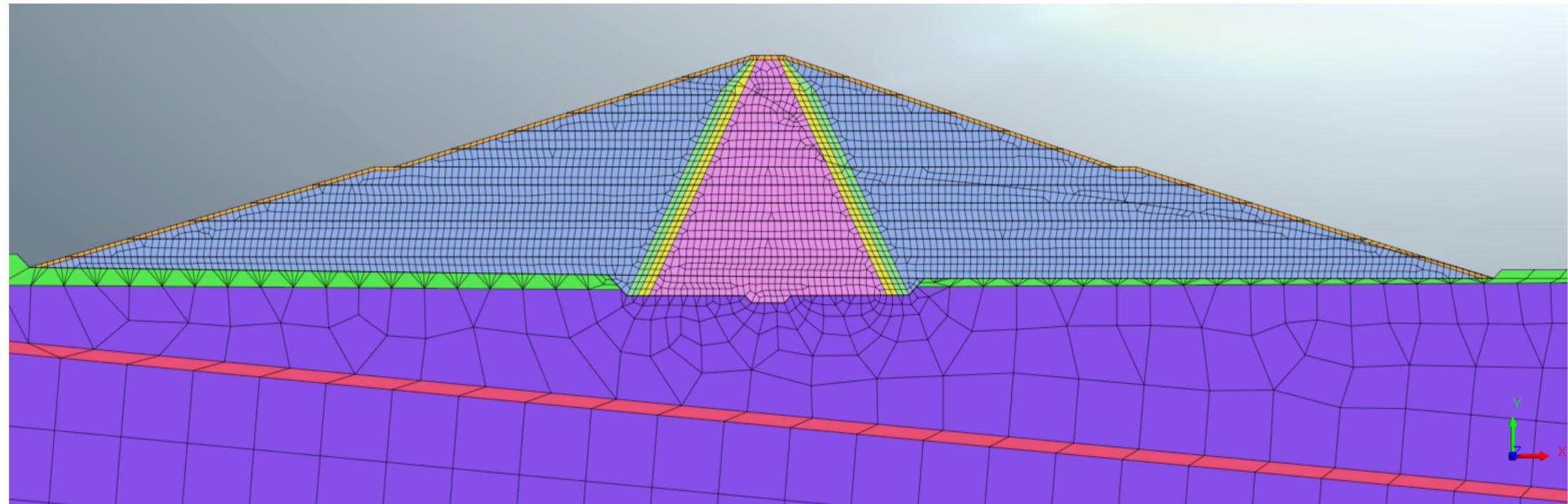
4,5,6) After fast meshing, define material properties to the mesh sets

7,8) Select layers and merge

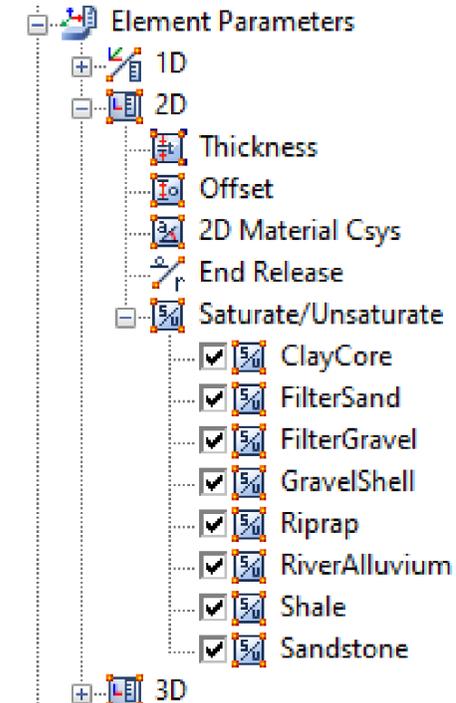
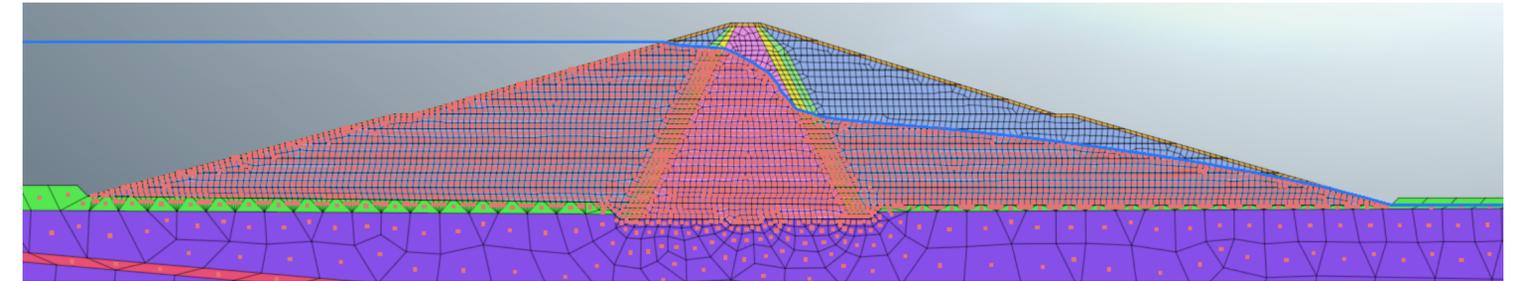
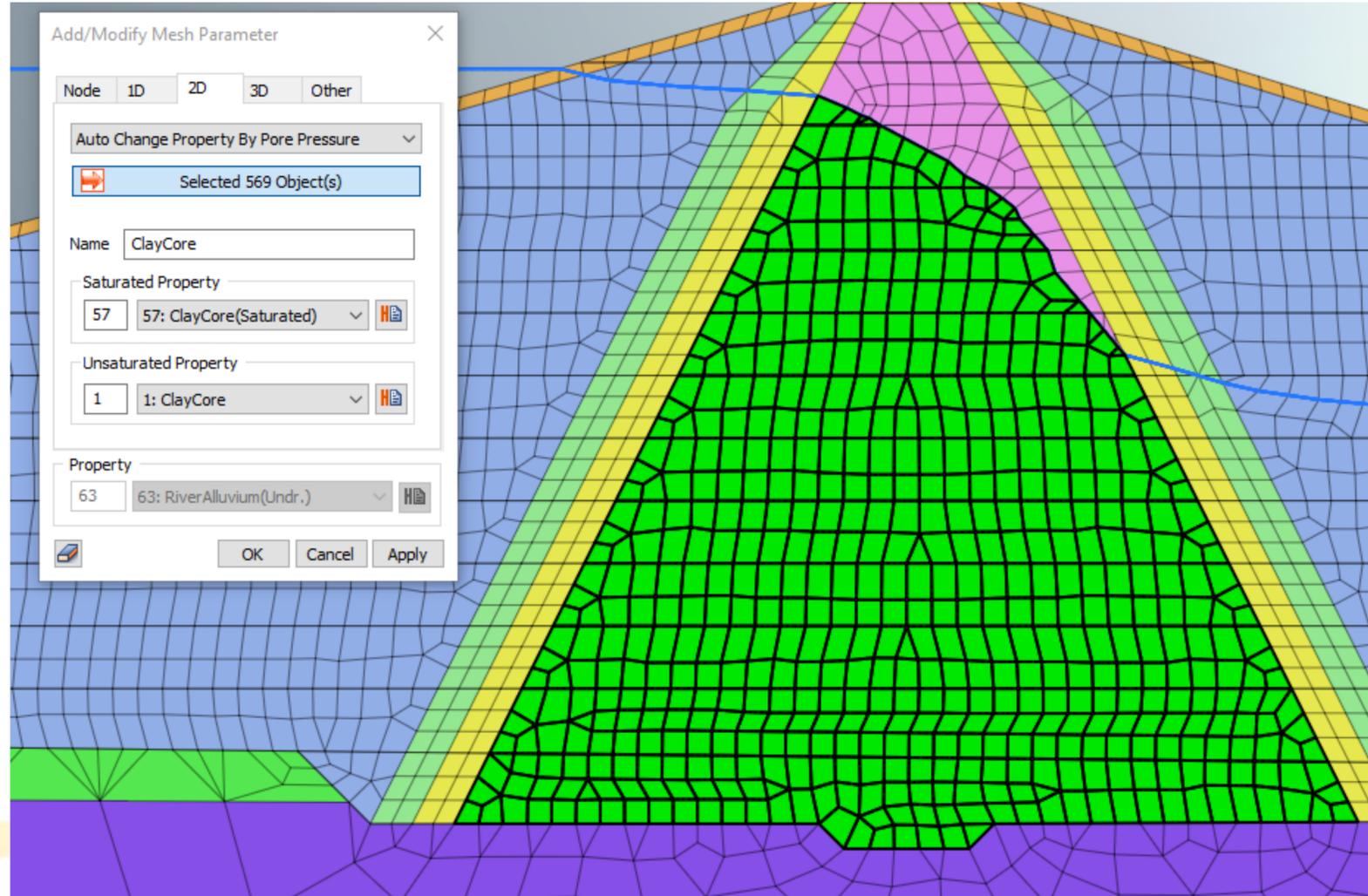
9) Select the layers and rename

Layers are properly defined.

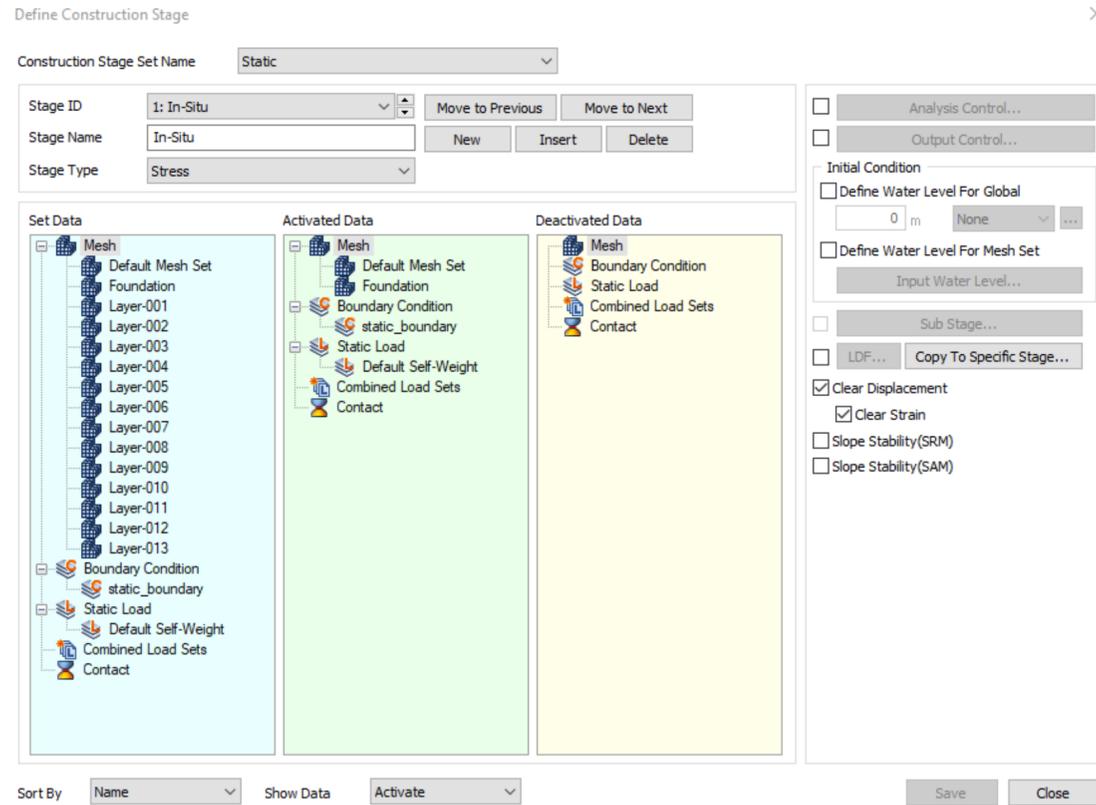
-  Layer-001
-  Layer-002
-  Layer-003
-  Layer-004
-  Layer-005
-  Layer-006
-  Layer-007
-  Layer-008
-  Layer-009
-  Layer-010
-  Layer-011
-  Layer-012
-  Layer-013



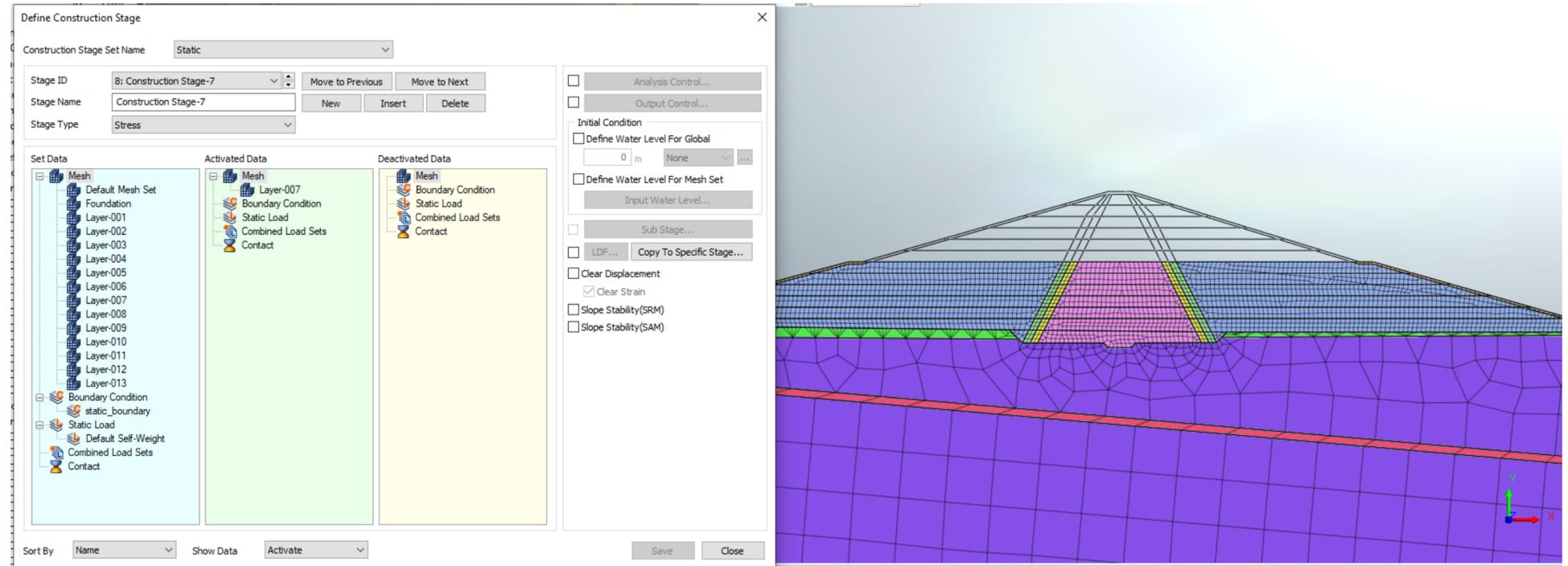
Auto Change of Saturated Material Parameters



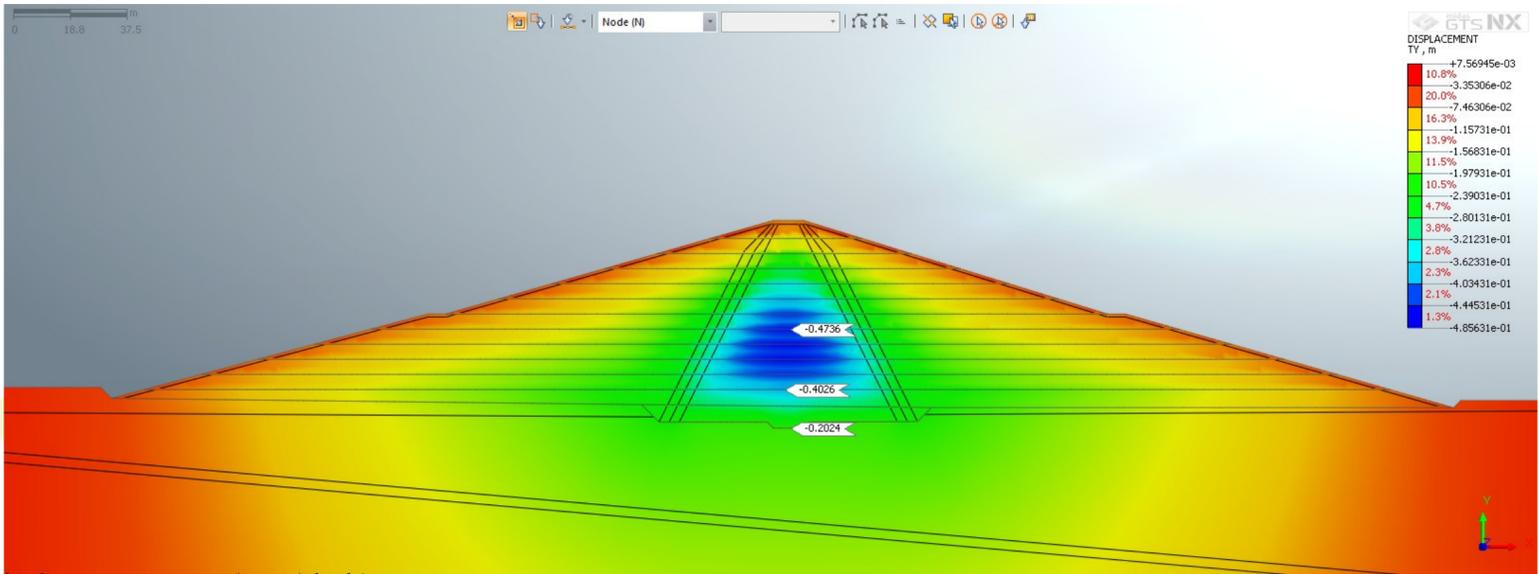
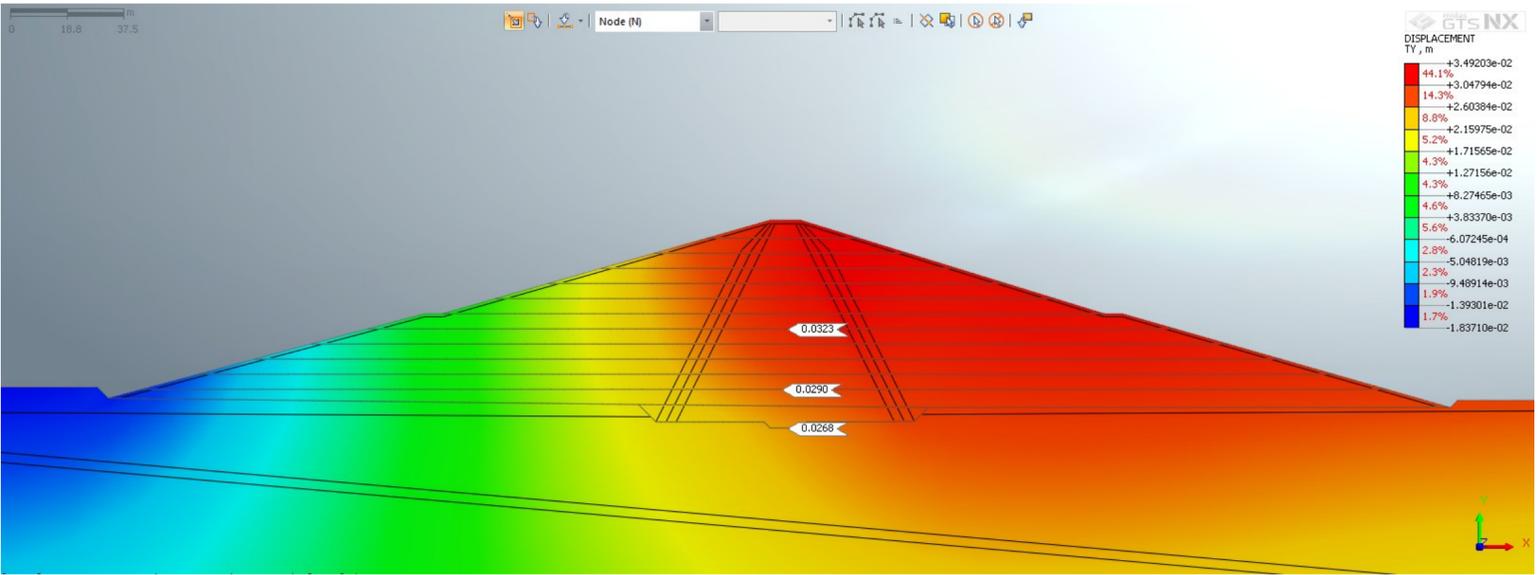
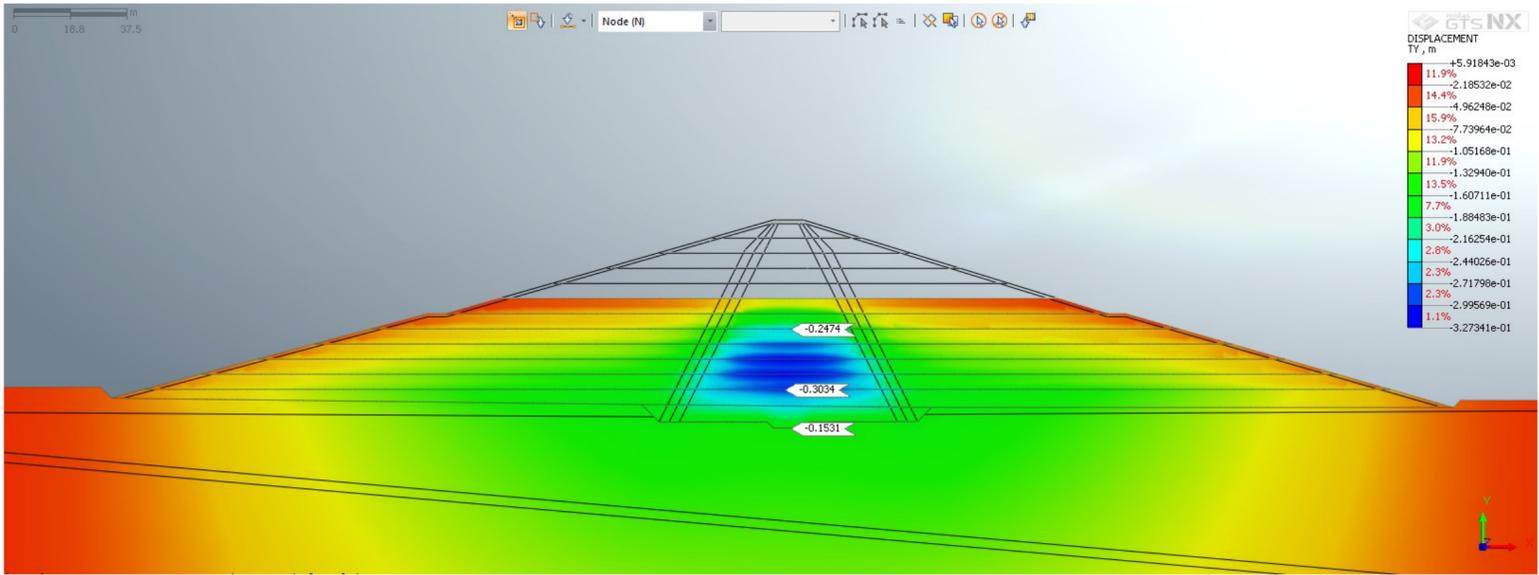
Auto Change of Saturated Material Parameters



By adding the layers step by step, we define the construction stages



Results



Analyses Type	Maximum Horizontal Deformation (m)	Maximum Vertical Deformation (m)
End of Construction	0.06	0.49
Impoundment	0.05	0.035

Challenges in Dynamic Stability

The project is in a seismically active zone.

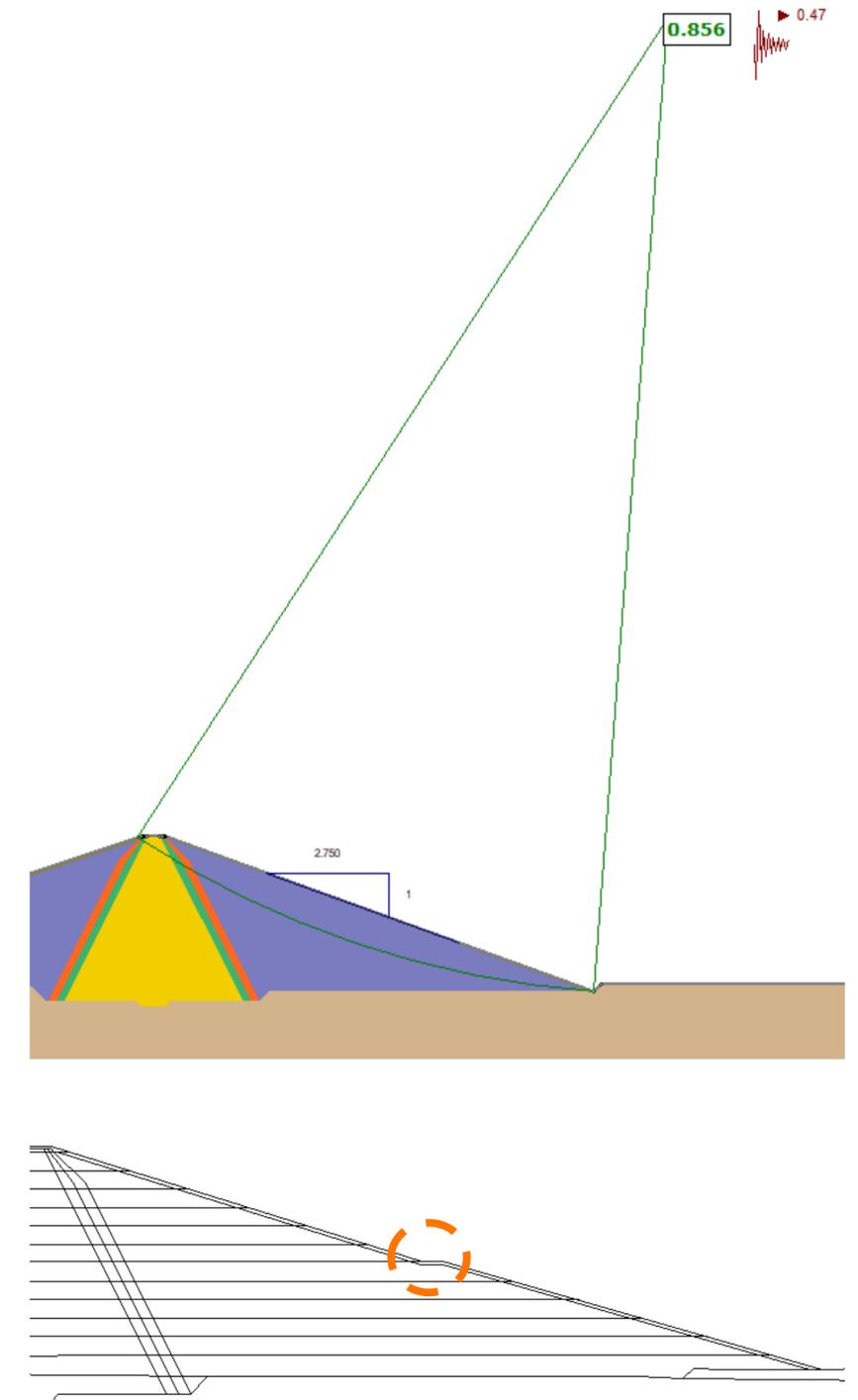
Recommended PGA value in Seismic Hazard Analysis

Report was 0.7g.

Initial design of the dam had no benches and slopes were too steep. Thus, factor of safety in pseudo-static method is lower than 1.

We **lowered the steepness of the slopes** and **put a bench in the middle** of it. It effected the dynamic stability greatly.

Static methods cannot capture oscillatory nature of earthquake ground motion, so dynamic analysis in a finite element software assess the seismic performance of the slopes better than limit-equilibrium methods.



Dynamic Analysis

Sloshing Medium

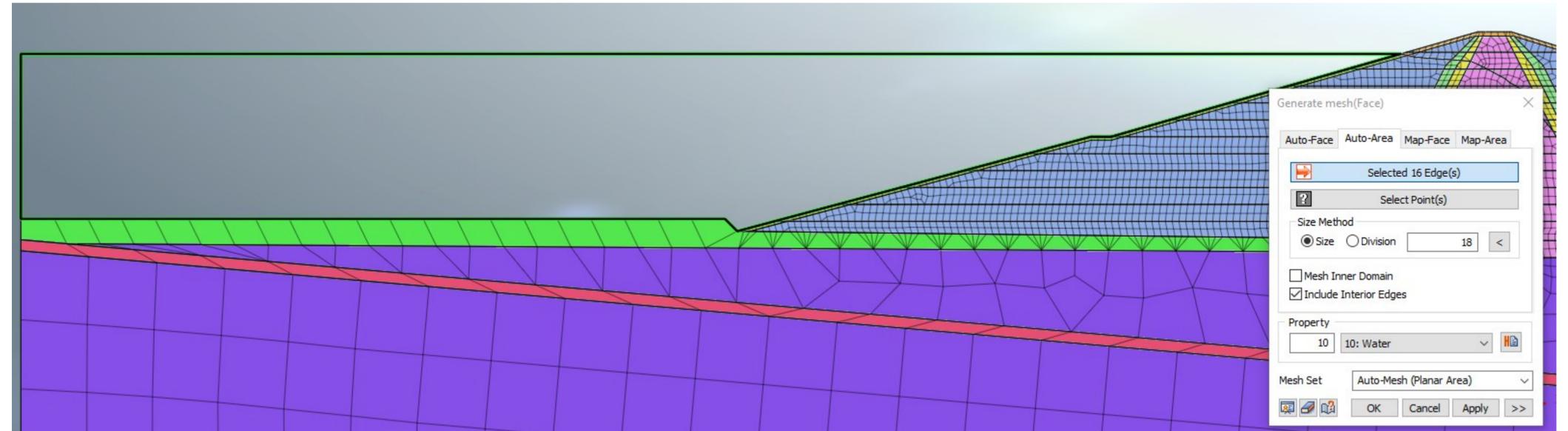
The water in the reservoir can be interpreted directly with a sloshing medium material and can be meshed easily as other materials.

Material ×

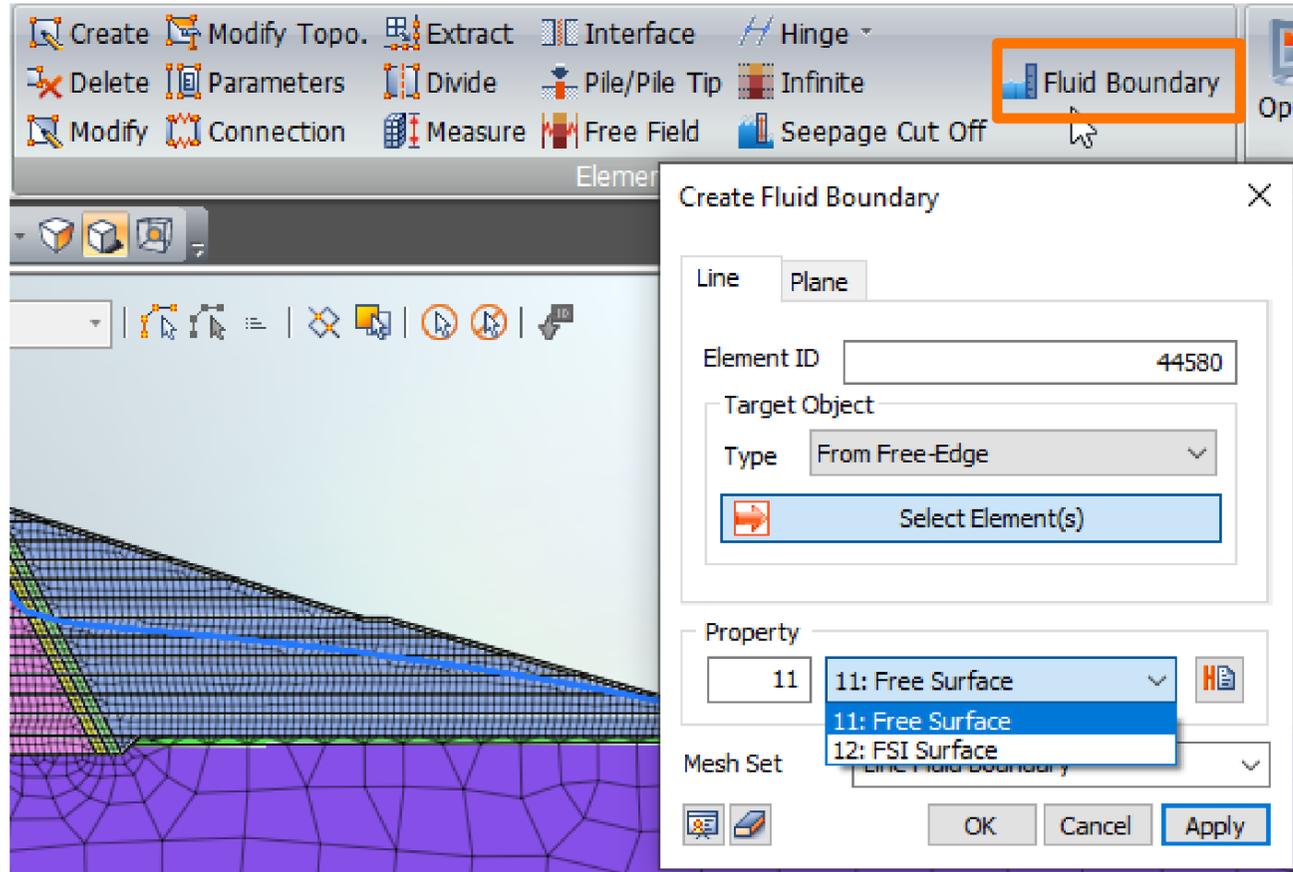
ID Name Color

Inviscid

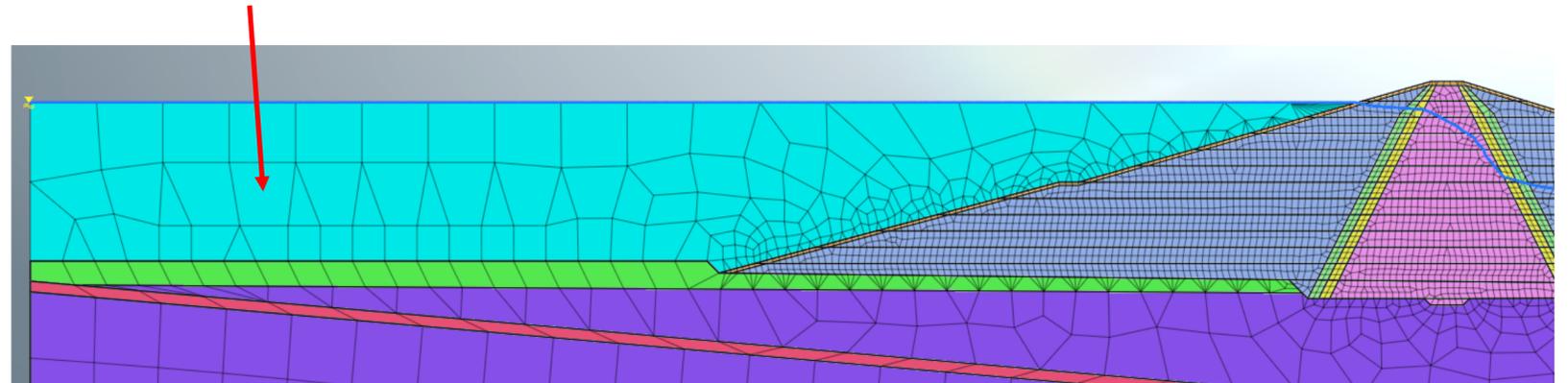
Bulk Modulus (k)	<input type="text" value="2200000"/>	kN/m ²
Unit Weight(γ)	<input type="text" value="9.80665"/>	kN/m ³



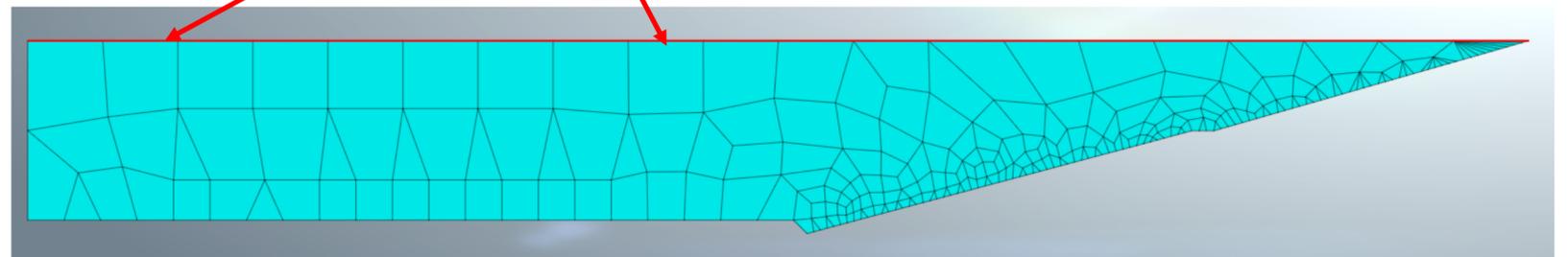
Sloshing Fluid Boundaries



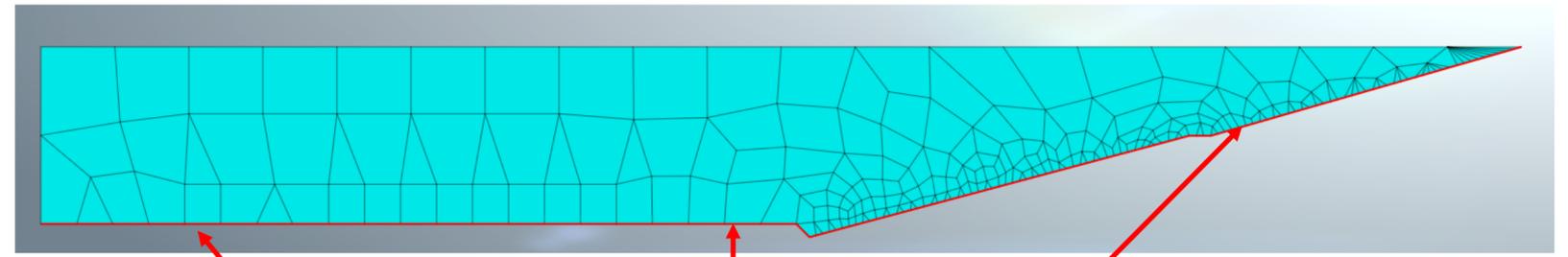
Sloshing Material (Water)



Free Surface

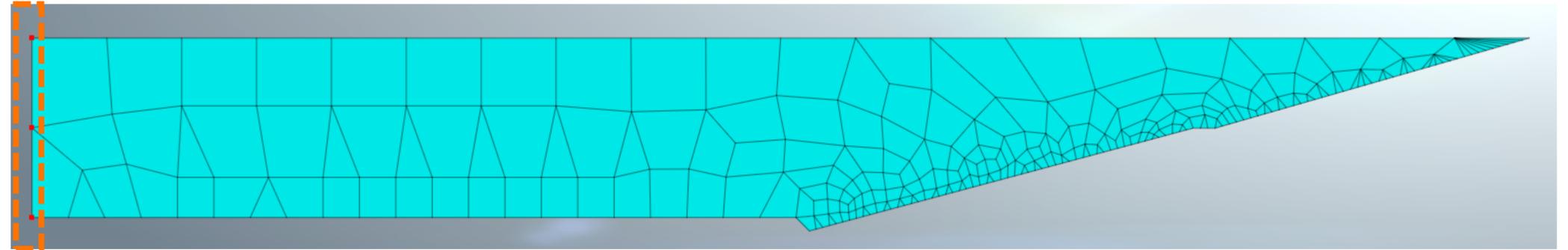
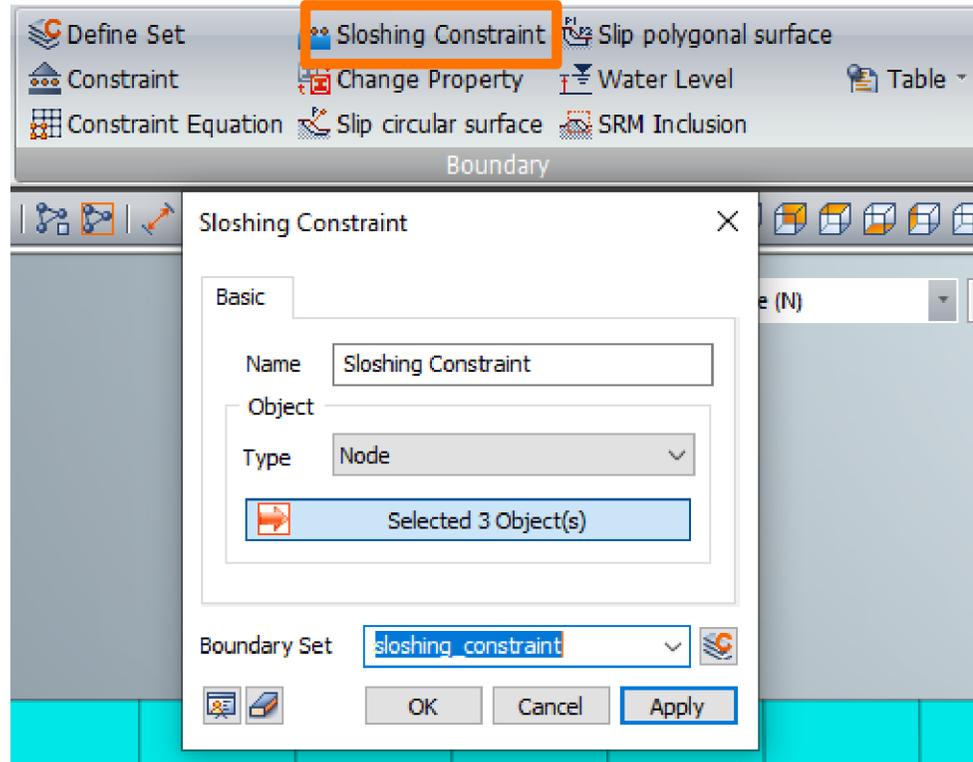


FSI (Fluid Structure Interaction) Boundary



Do not forget to close other meshes while defining fluid boundaries!!

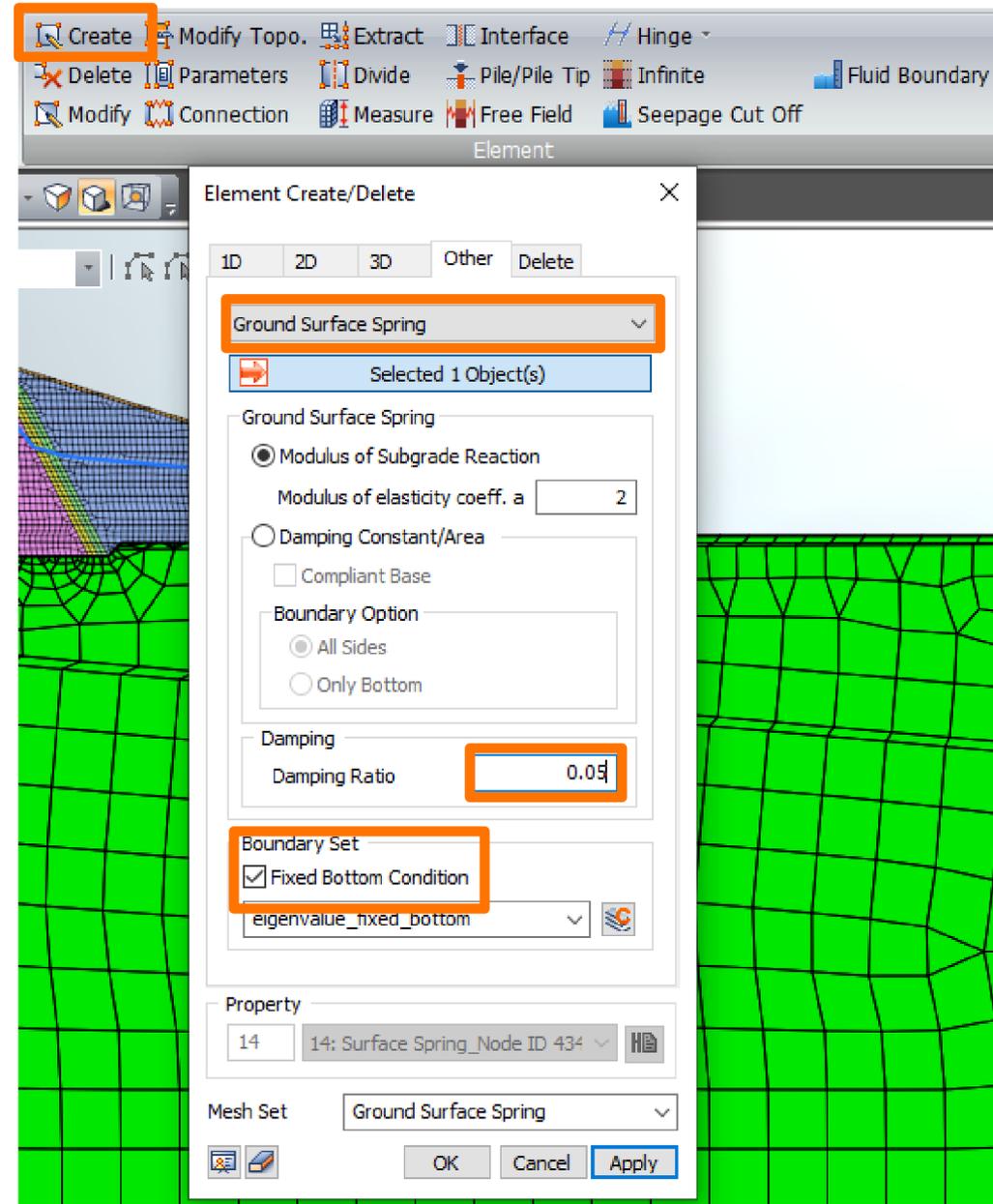
Sloshing Fluid Boundaries



Sloshing constraint will simulate our long reservoir.

Eigenvalue Analysis

Boundary conditions for eigenvalue analysis



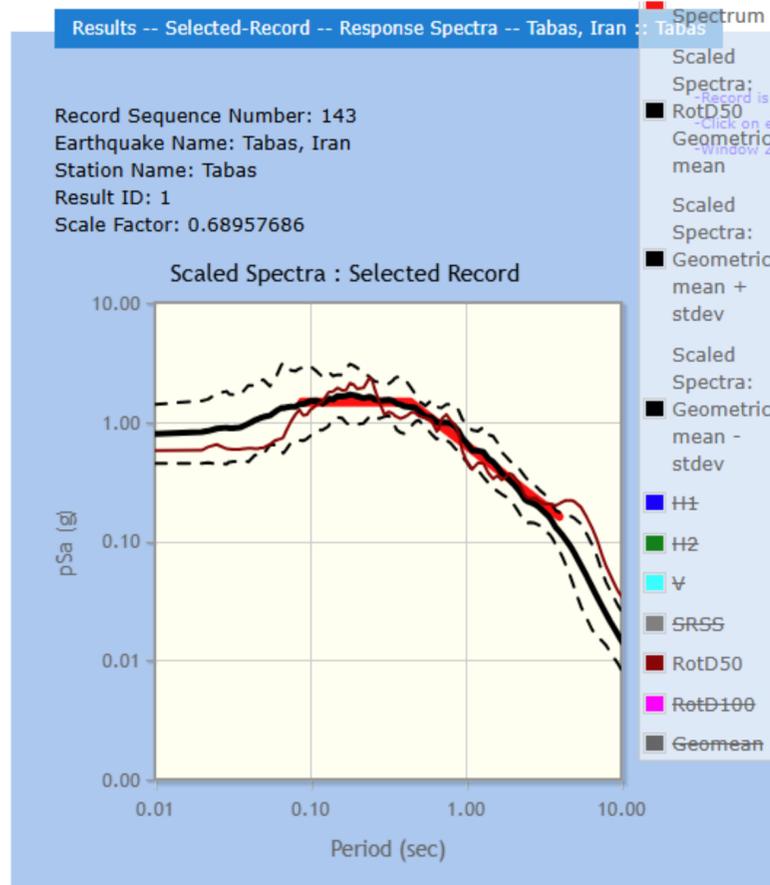
Eigenvalue Analysis

Results of Eigenvalue Analysis

PERCENTAGE MODAL EFFECTIVE MASS						
MODE NUMBER	T1	T2	T3	R1	R2	R3
1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
7	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
8	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
9	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
10	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
11	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
12	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
13	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
14	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
15	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
16	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
17	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
18	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
19	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
21	42.01%	0.01%	0.00%	0.00%	0.00%	3.38%
22	0.33%	28.51%	0.00%	0.00%	0.00%	0.68%
23	15.36%	0.02%	0.00%	0.00%	0.00%	15.73%
24	2.47%	23.77%	0.00%	0.00%	0.00%	12.80%
25	1.66%	8.18%	0.00%	0.00%	0.00%	28.34%
26	4.45%	1.95%	0.00%	0.00%	0.00%	3.46%
27	0.32%	8.88%	0.00%	0.00%	0.00%	8.24%
28	0.07%	1.51%	0.00%	0.00%	0.00%	0.01%
29	0.01%	0.41%	0.00%	0.00%	0.00%	0.04%
30	0.00%	0.03%	0.00%	0.00%	0.00%	0.03%

REAL EIGENVALUES									
MODE NUMBER	EIGENVALUE	RADIANS	CYCLES	PERIOD	GENERALIZED MASS	GENERALIZED STIFFNESS	ORTHOGONALITY LOSS	DAMPING RATIO	ERROR MEASURE
1	6.477510e-03	8.048298e-02	1.280926e-02	7.806850e+01	1.000000e+00	6.477621e-03	0.000000e+00	2.107892e-04	3.925289e-05
2	3.933161e-02	1.983220e-01	3.156392e-02	3.168174e+01	1.000000e+00	3.933165e-02	4.758566e-10	1.548666e-04	3.290301e-05
3	9.487437e-02	3.080168e-01	4.902240e-02	2.039884e+01	1.000000e+00	9.487439e-02	2.430595e-10	1.081781e-04	2.488076e-05
4	1.637171e-01	4.046197e-01	6.439723e-02	1.552862e+01	1.000000e+00	1.637171e-01	1.271763e-10	7.212051e-05	1.056370e-04
5	2.468048e-01	4.967945e-01	7.906730e-02	1.264745e+01	1.000000e+00	2.468048e-01	8.116836e-11	4.784516e-05	8.520322e-05
6	3.333726e-01	5.773843e-01	9.189356e-02	1.088215e+01	1.000000e+00	3.333726e-01	4.904306e-11	3.255636e-05	1.785699e-04
7	4.256966e-01	6.524543e-01	1.038413e-01	9.630077e+00	1.000000e+00	4.256966e-01	3.017255e-11	2.241015e-05	1.578177e-04
8	5.239957e-01	7.238755e-01	1.152084e-01	8.679925e+00	1.000000e+00	5.239957e-01	1.881045e-11	1.607212e-05	3.394021e-04
9	6.238210e-01	7.898234e-01	1.257043e-01	7.955178e+00	1.000000e+00	6.238210e-01	1.322364e-11	1.362619e-05	5.912413e-04
10	7.343063e-01	8.569168e-01	1.363825e-01	7.332317e+00	1.000000e+00	7.343063e-01	8.821860e-12	8.362906e-06	5.244250e-04
11	8.576922e-01	9.261168e-01	1.473961e-01	6.784442e+00	1.000000e+00	8.576922e-01	5.472428e-12	7.852995e-06	6.917979e-04
12	9.831250e-01	9.915266e-01	1.578064e-01	6.336880e+00	1.000000e+00	9.831250e-01	4.106715e-12	6.094980e-06	6.845631e-04
13	1.128190e+00	1.062163e+00	1.690485e-01	5.915463e+00	1.000000e+00	1.128190e+00	2.541939e-12	5.393423e-06	6.644407e-04
14	1.266284e+00	1.125293e+00	1.790960e-01	5.583599e+00	1.000000e+00	1.266284e+00	1.515885e-12	3.575194e-06	8.893130e-04
15	1.439023e+00	1.199593e+00	1.909211e-01	5.237765e+00	1.000000e+00	1.439023e+00	0.000000e+00	1.677534e-06	6.730900e-04
16	1.636861e+00	1.279398e+00	2.036226e-01	4.911046e+00	1.000000e+00	1.636861e+00	0.000000e+00	1.809273e-06	6.076087e-04
17	1.745193e+00	1.321058e+00	2.102528e-01	4.756178e+00	1.000000e+00	1.745193e+00	0.000000e+00	1.795591e-06	8.392700e-04
18	1.952568e+00	1.397343e+00	2.223940e-01	4.496525e+00	1.000000e+00	1.952568e+00	0.000000e+00	6.240470e-08	3.428298e-04
19	2.156935e+00	1.468651e+00	2.337430e-01	4.278202e+00	1.000000e+00	2.156935e+00	0.000000e+00	2.020236e-08	2.641093e-04
20	2.385573e+00	1.544520e+00	2.458106e-01	4.068024e+00	1.000000e+00	2.385573e+00	0.000000e+00	1.573296e-07	2.746702e-04
21	8.095877e+00	2.845325e+00	4.528476e-01	2.208248e+00	1.000000e+00	8.095877e+00	3.326867e-11	4.998208e-02	1.276823e-07
22	1.457194e+01	3.817321e+00	6.075455e-01	1.645967e+00	1.000000e+00	1.457194e+01	1.348566e-11	4.991681e-02	1.556809e-07
23	1.579911e+01	3.974809e+00	6.326105e-01	1.580752e+00	1.000000e+00	1.579911e+01	1.820381e-10	4.995618e-02	1.406419e-07
24	1.952498e+01	4.418708e+00	7.032593e-01	1.421951e+00	1.000000e+00	1.952498e+01	8.465676e-12	4.992328e-02	7.297464e-08
25	2.249827e+01	4.743234e+00	7.549091e-01	1.324663e+00	1.000000e+00	2.249827e+01	5.355398e-12	4.998887e-02	5.223417e-08
26	2.339872e+01	4.837223e+00	7.698679e-01	1.298924e+00	1.000000e+00	2.339872e+01	5.890728e-11	4.994335e-02	1.107506e-07
27	2.387997e+01	4.886714e+00	7.777446e-01	1.285769e+00	1.000000e+00	2.387997e+01	2.663863e-10	4.999346e-02	5.430897e-08
28	2.767312e+01	5.260524e+00	8.372385e-01	1.194403e+00	1.000000e+00	2.767312e+01	2.764245e-10	4.995070e-02	1.204253e-07
29	3.275437e+01	5.723144e+00	9.108666e-01	1.097856e+00	1.000000e+00	3.275437e+01	9.526978e-11	4.995829e-02	6.407128e-08
30	3.431491e+01	5.857893e+00	9.323126e-01	1.072602e+00	1.000000e+00	3.431491e+01	3.994921e-11	4.998261e-02	2.980938e-08

Choosing and Defining a Dynamic Load Input



ngawest2.berkeley.edu

Ground Acceleration

Name: Tabas Iran H1

X Direction
 Function: RSN143_H1
 Scale Factor: 1
 Arrival Time: 0 sec

Y Direction
 Function: RSN143_V
 Scale Factor: 1
 Arrival Time: 0 sec

Z Direction
 Function: None (Constant)
 Scale Factor: 1
 Arrival Time: 0 sec

Dynamic Load Set: Tabas Iran H1

Time Forcing Function

Name	Type	Data Type
RSN143_H1	Time Function	Norm. Acc.
RSN143_H2	Time Function	Norm. Acc.
RSN143_V	Time Function	Norm. Acc.
RSN779_H1	Time Function	Norm. Acc.
RSN779_H2	Time Function	Norm. Acc.
RSN779_V	Time Function	Norm. Acc.

Time History Load Function

Name: RSN143_H1

Time Function Data Type: Normalized Acceleration

Scaling: Scale Factor: 1
 Max. Value: 0 g

Self Weight: 9.80665 m/sec²

Time (sec)	Value (g)
0	0.0065085
0.02	0.0065139
0.04	0.0065429
0.06	0.0065985
0.08	0.0065243
0.1	0.0063879
0.12	0.0065127
0.14	0.0066078
0.16	0.0062201
0.18	0.0058871
0.2	0.0061952
0.22	0.0063434

Graph Option: X-axis Log Scale
 Y-axis Log Scale

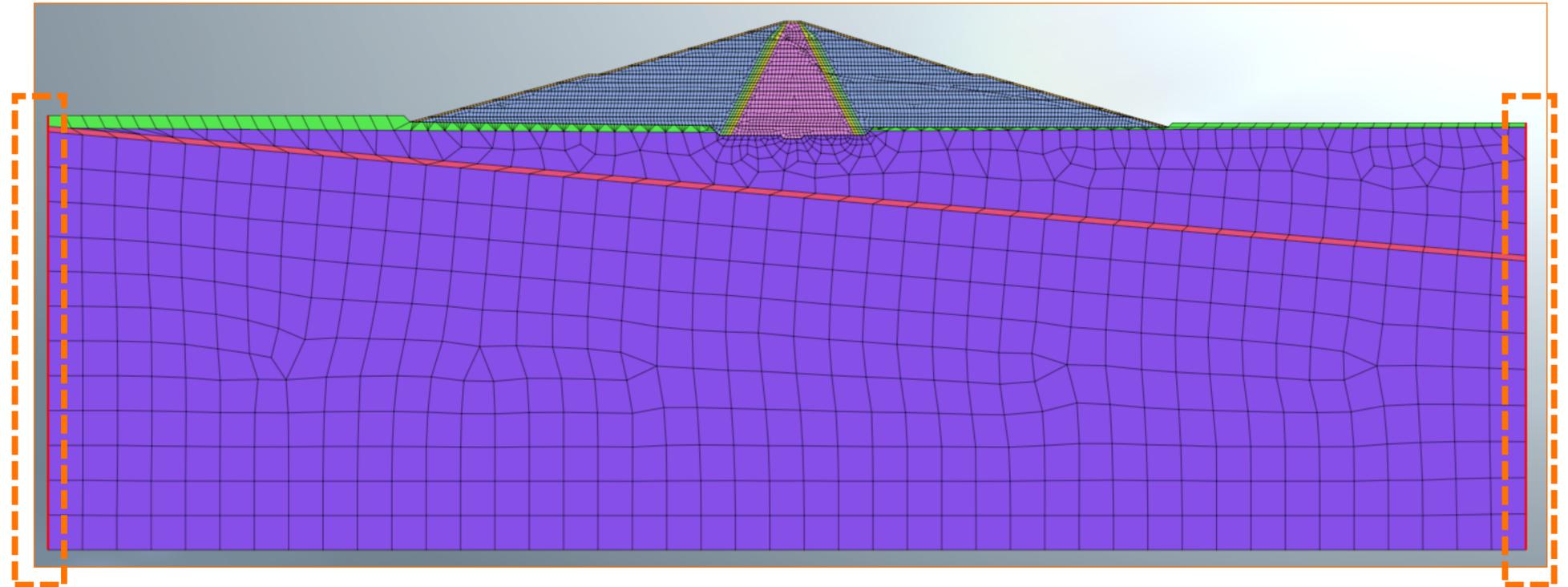
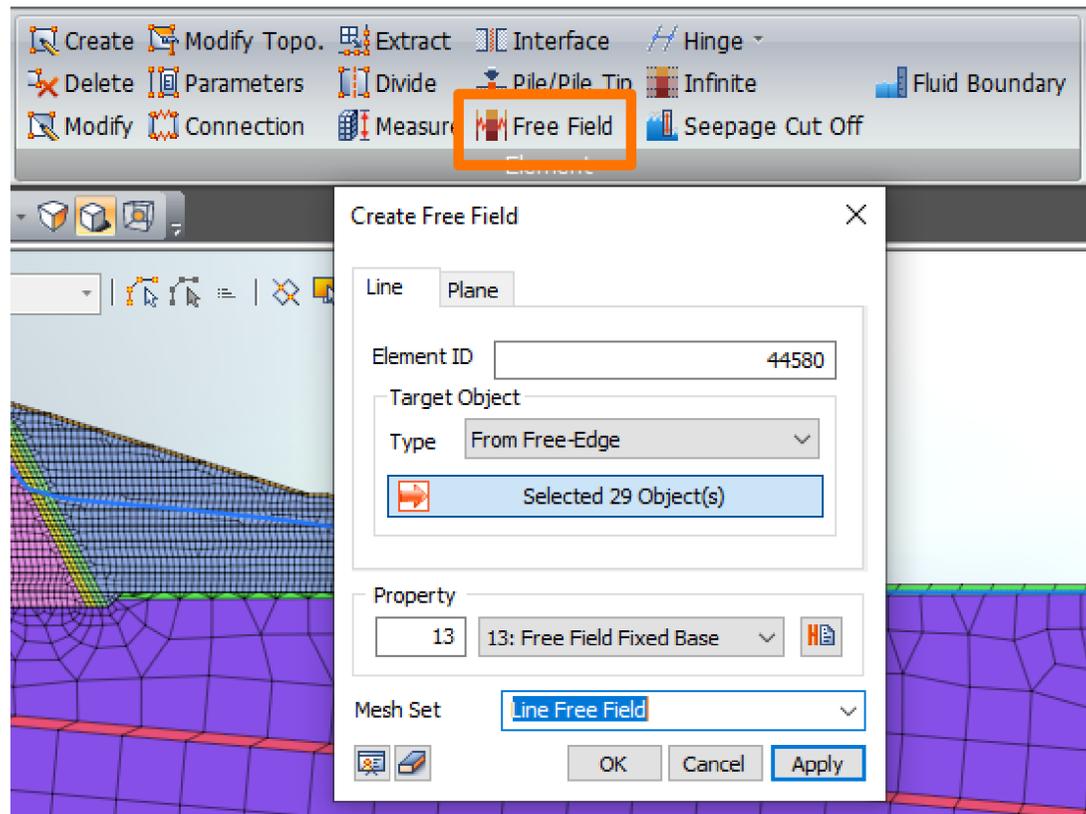
Baseline Correction: Original Consider

Description: Tabas Iran, 9/16/1978, H1

[Dynamic Analysis]
 > [Ground Acceleration]
 > [Time Forcing Function]
 > [Add Time Function]
 and copy/paste the
 selected acceleration-time
 history recording.

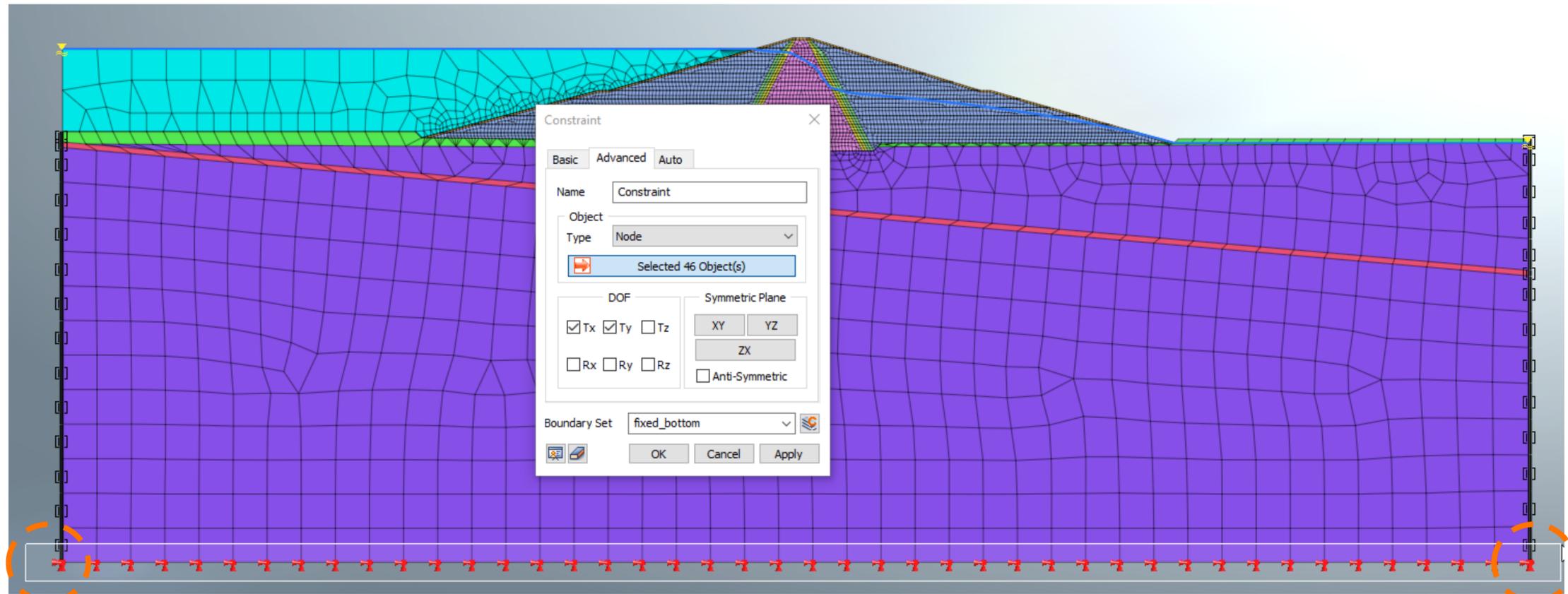
Boundary Conditions for Dynamic Analysis

Free field conditions should be applied to the sides to simulate the infinite ground.



Boundary Conditions for Dynamic Analysis

Fixed boundary conditions for bottom are used for this analysis.



Caution: Bottom node of free field elements have to be fixed!

Preparation of Dynamic Step of Construction Stages

The steps before the dynamic step is identical to the static analysis.

Here we add additional mesh sets and boundary conditions for sloshing material and SRM for post-earthquake slope stability check.

Define Construction Stage

Construction Stage Set Name: Tabas Iran H1

Stage ID: 16: Tabas-Iran-H1 | Move to Previous | Move to Next

Stage Name: Tabas-Iran-H1 | New | Insert | Delete

Stage Type: Nonlinear Time History | Time Step...

Set Data: Mesh, Default Mesh Set, FSI Surface, Foundation, Free Field Fixed, Free Surface, Layer-001 to Layer-013, Water, eigenvalue_springs, Boundary Condition, SRM_inclusion, eigenvalue_fixed_bott..., fixed_bottom

Activated Data: Mesh, FSI Surface, Free Surface, Water, Boundary Condition, sloshing_constraint, Boundary Condition (for SRM), SRM_inclusion, sm_boundary, Combined Load Sets, Dynamic Load, Tabas Iran H1

Deactivated Data: Mesh, Boundary Condition, Combined Load Sets, Dynamic Load, Contact

Analysis Control... [checked]

Output Control... [checked]

Initial Condition: 0 m | None | ...

Define Water Level For Global [unchecked]

Define Water Level For Mesh Set [unchecked]

Input Water Level...

Slope Stability(SRM) [checked]

Sort By: Name | Show Data: Activate

Save | Close

Defining SRM Inclusion & Post-Earthquake SRM Analysis

After SRM Inclusion zone has been defined; SRM tick in the dynamic construction stage analysis options should be activated.

Later on, in analysis control the latest second of the acceleration-time history should be written to check slope stability with post-earthquake stresses.

The image displays three screenshots from a software interface, likely a finite element analysis (FEA) program, illustrating the configuration of SRM Inclusion and Analysis Control.

SRM Inclusion Dialog: This dialog box is used to define the SRM Inclusion zone. The "Name" field is set to "SRM Inclusion-3". The "Object" field is empty, and the "Boundary Set" dropdown menu is set to "SRM_inclusion". The "Apply" button is highlighted.

Analysis Control Dialog: This dialog box is used to control the analysis. The "Slope Stability(SRM)" tab is selected. The "Define Time" table is shown below:

No	Time	
1	32.98	

The "Slope Stability(SRM)" checkbox is checked. The "Advanced Nonlinear Parameters..." button is visible at the bottom.

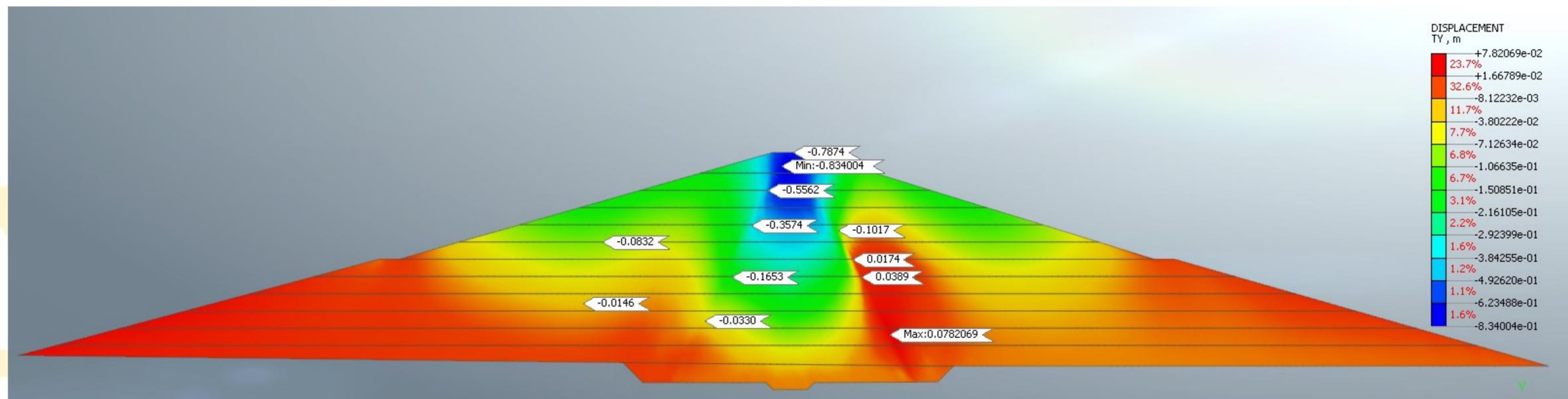
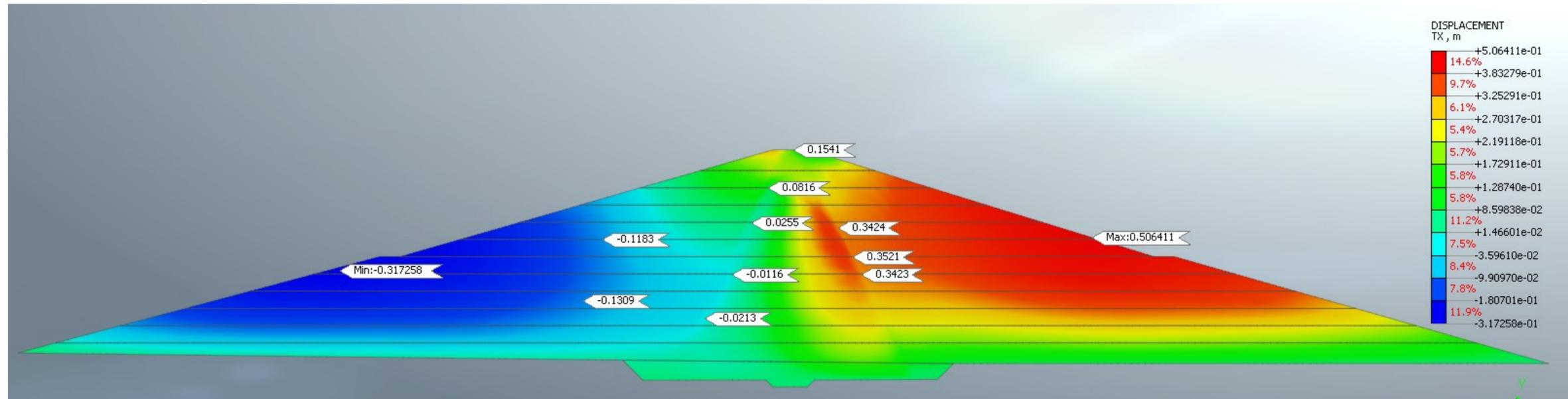
Analysis Control - Slope Stability(SRM) Sub-dialog: This sub-dialog box is used to configure the parameters for the SRM analysis. The "Define Time" table is shown below:

No	Time	
1	32.98	

The "Slope Stability(SRM)" checkbox is checked. The "Advanced Nonlinear Parameters..." button is visible at the bottom.

Results of Dynamic Analysis

The displacement results can be selected for both directions and can be easily read by probe selection, node by node.



Evaluation of the Results

In table on the top, evaluation according to Pells and Fell (2002) is given. It only gives thresholds and related damage states of the dam.

Analysis Type	Earthquake	Vertical Disp. (m)	Relative Settlement (%)	Minor Damage
End of Construction	Tabas Iran H1	0.54	0.78	Major
	Tabas Iran H2	0.38	0.55	Major
	Loma Prieta H1	1.07	1.56	Severe
	Loma Prieta H2	0.27	0.39	Moderate
	Northridge H1	0.21	0.31	Moderate
	Northridge H2	0.21	0.31	Moderate
Impoundment	Tabas Iran H1	0.75	1.09	Major
	Tabas Iran H2	0.77	1.12	Major
	Loma Prieta H1	1.08	1.57	Severe
	Loma Prieta H2	0.54	0.78	Major
	Northridge H1	0.27	0.39	Moderate
	Northridge H2	0.43	0.63	Major

In the next table, more recent study of He and Rathje (2024) was used and they use a probabilistic approach to calculate the damage states and gives an occurrence probability.

Analysis Type	Earthquake	Vertical Disp. (m)	Relative Settlement (%)	Minor Damage	Moderate Damage	Severe Damage
End of Construction	Tabas Iran H1	0.54	0.78	1.00	0.71	0.12
	Tabas Iran H2	0.38	0.55	1.00	0.57	0.06
	Loma Prieta H1	1.07	1.56	1.00	0.89	0.34
	Loma Prieta H2	0.27	0.39	1.00	0.44	0.03
	Northridge H1	0.21	0.31	0.99	0.34	0.01
	Northridge H2	0.21	0.31	0.99	0.34	0.01
Impoundment	Tabas Iran H1	0.75	1.09	1.00	0.81	0.21
	Tabas Iran H2	0.77	1.12	1.00	0.82	0.22
	Loma Prieta H1	1.08	1.57	1.00	0.89	0.34
	Loma Prieta H2	0.54	0.78	1.00	0.71	0.12
	Northridge H1	0.27	0.39	1.00	0.44	0.03
	Northridge H2	0.43	0.63	1.00	0.62	0.08

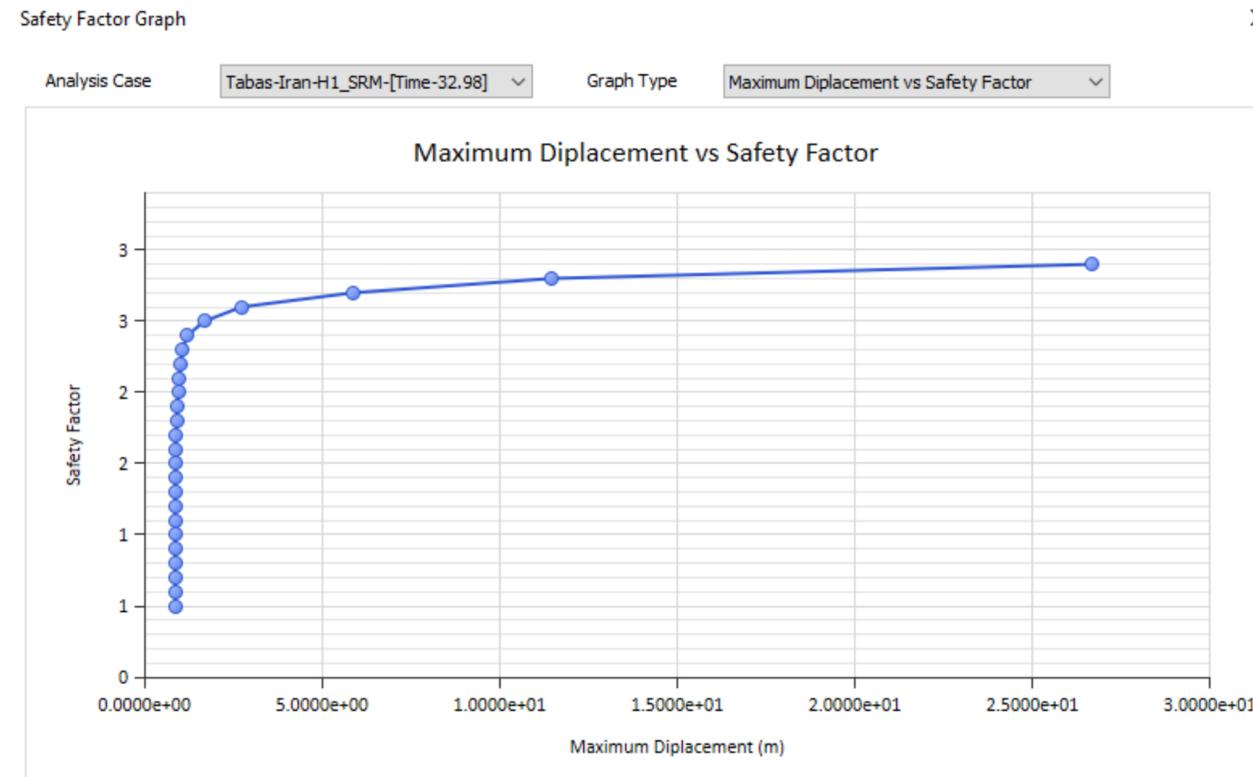
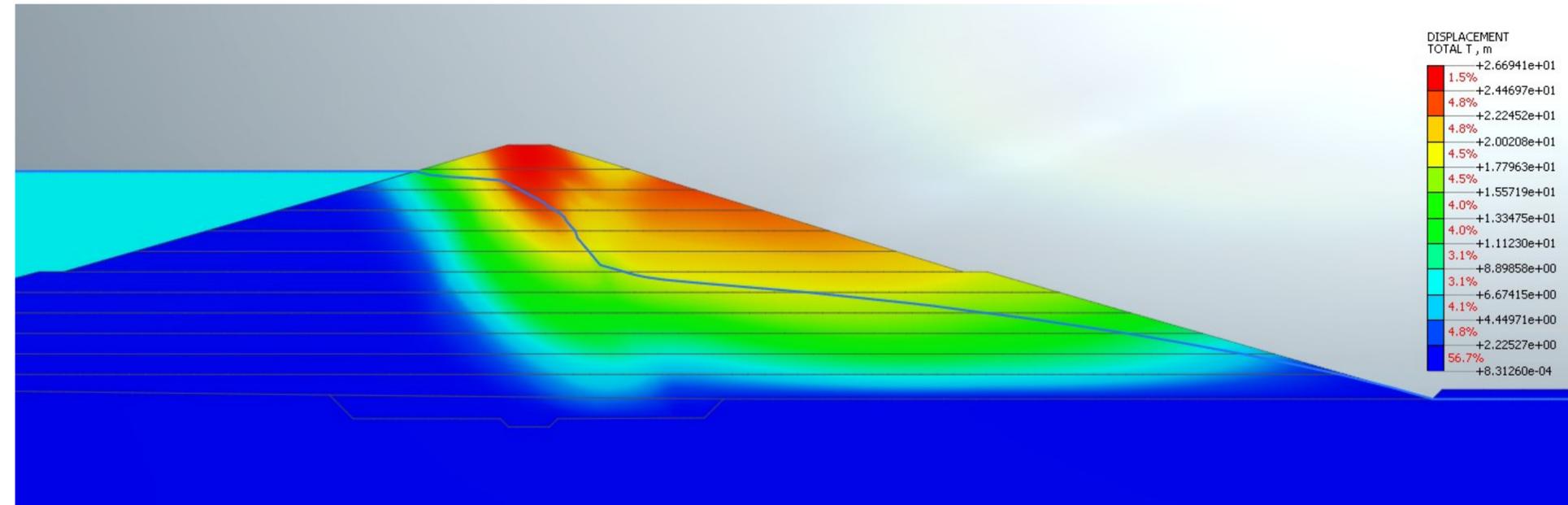
Results of SRM

The SRM involves modelling subsurface materials as elastic-perfectly-plastic materials, while simultaneously reducing strengths by a strength reduction factor, R.

$$c_d = \frac{c}{R}$$

$$\tan(\phi_d) = \frac{\tan(\phi)}{R}$$

$$FOS = R_{max}$$



Analysis Type	Earthquake	F.S. After Earthquake with SRM
End of Construction	Tabas H1	2.75
	Tabas H2	3.2
	Loma Prieta H1	2.1
	Loma Prieta H2	2.5
	Cape Mendocino H1	3.05
	Cape Mendocino H2	2.8
Impoundment	Tabas H1	2.9
	Tabas H2	2.5
	Loma Prieta H1	3.4
	Loma Prieta H2	3
	Cape Mendocino H1	2.8
	Cape Mendocino H2	2.65