Session 2.

Ensuring Earthfill Dam Safety in Seismic Zones

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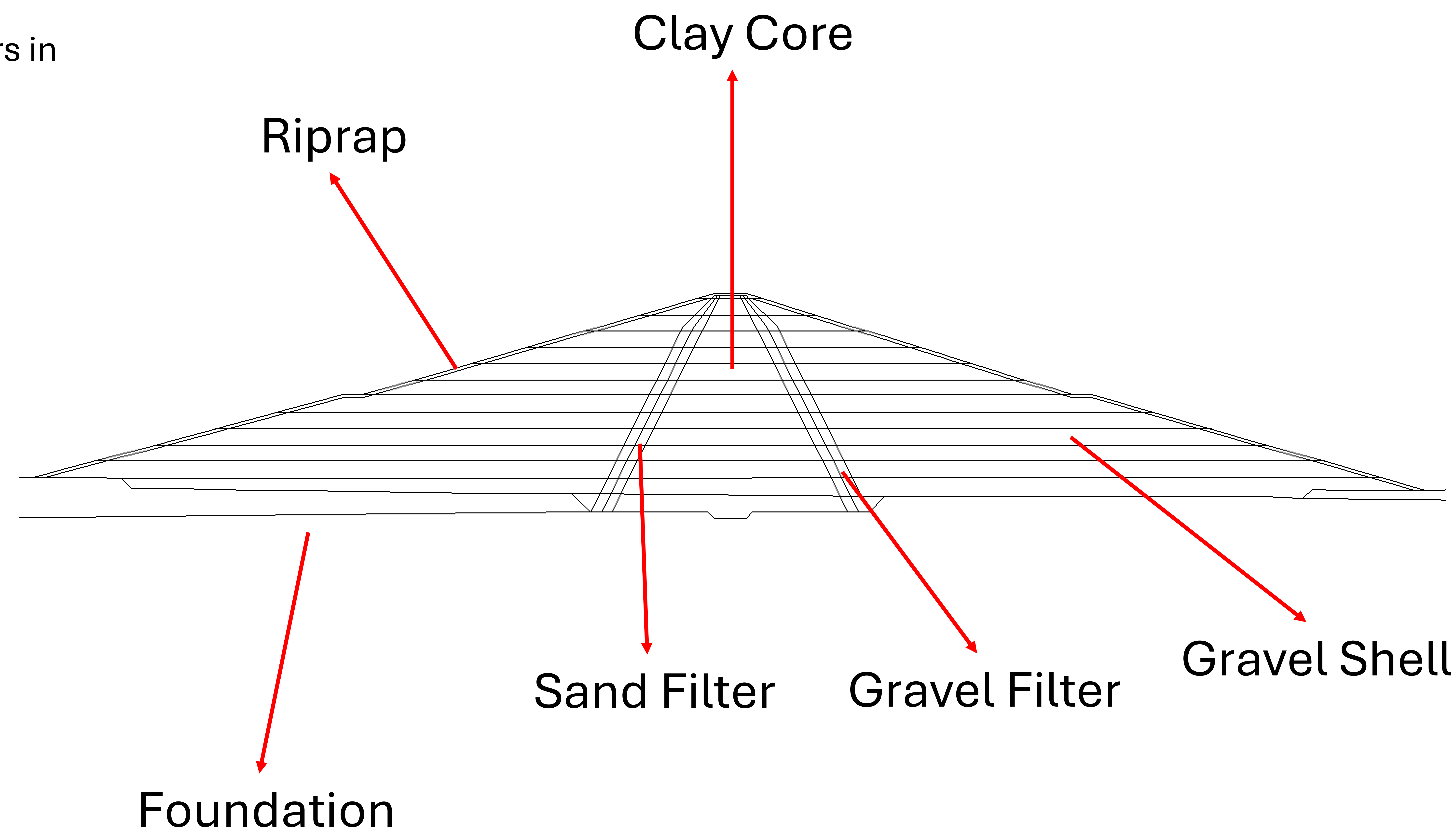
Introduction

- Embankment dam that we will analyze is 66.8 meters in height.

- Section includes:
  - Clay core
  - Sand filter
  - Gravel filter
  - Gravel shell
  - Riprap

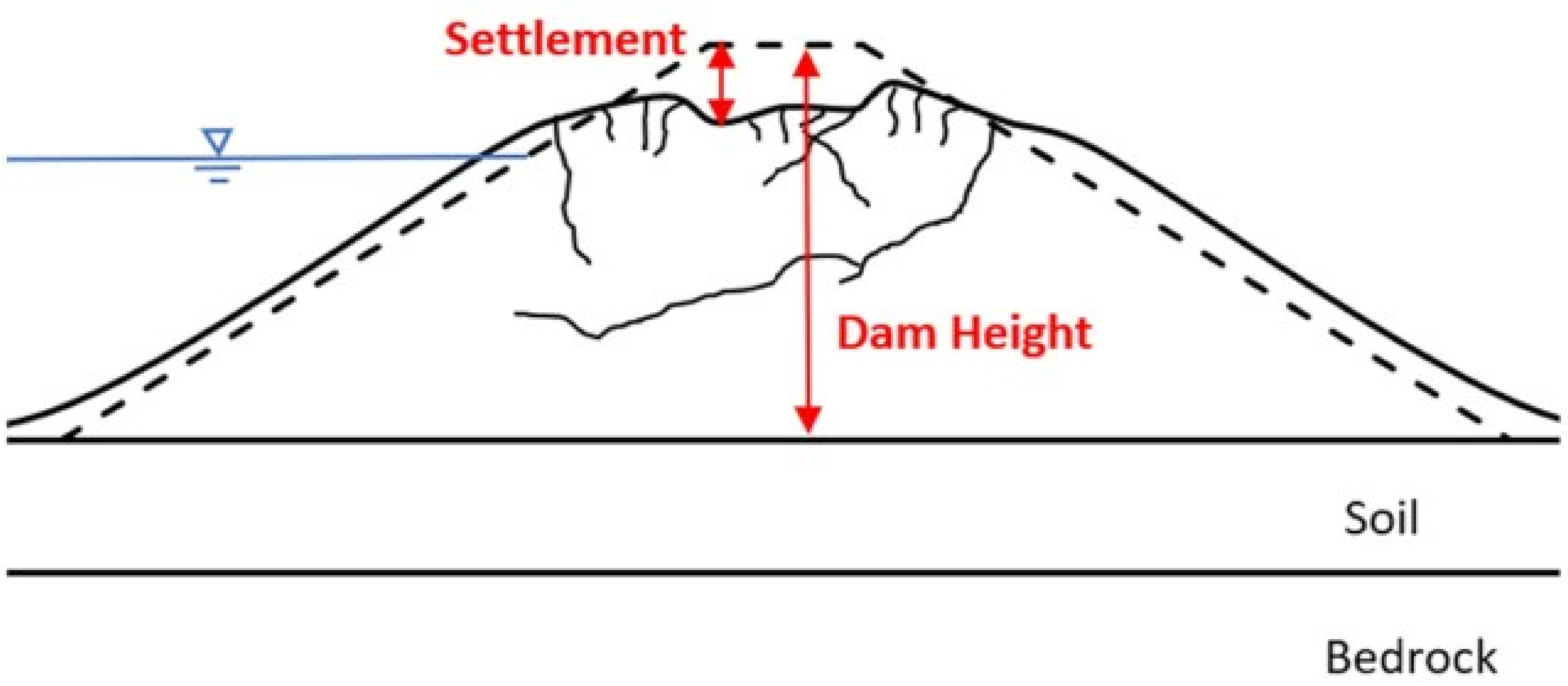


Seismic Induced Damages

- 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)

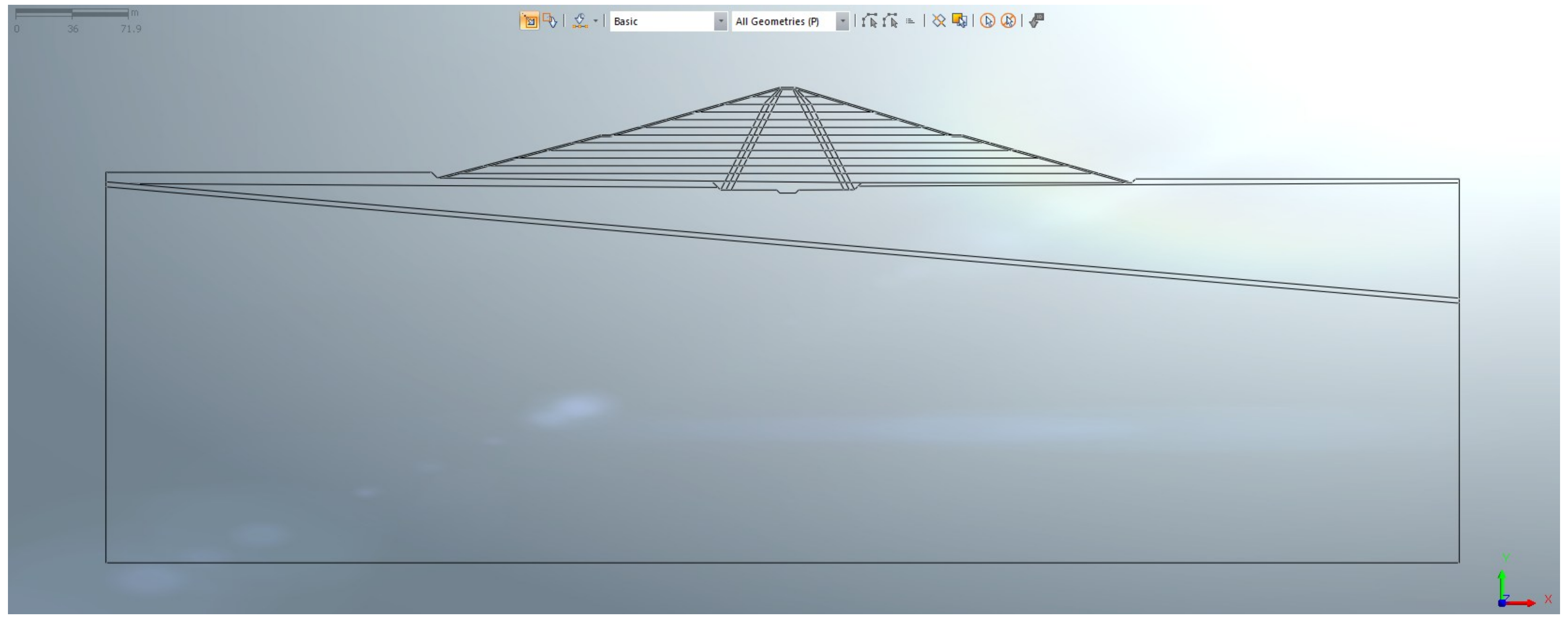
$$P_{DS}(RS) = \Phi\left[\frac{\ln(RS) - \mu_{\ln C}}{\sigma_{\ln C}}\right]$$

Material Properties

Name	E (kPa)	v	γ (kN/m^3)	γ_sat (kN/m^3)	E50ref (kPa)	Eoedref (kPa)	Eurref (kPa)	Failure Ratio	Ref. Pressure (Pref) (kPa)	Power of Stress Level Dependency	Internal Friction Angle (Φ)	Dilatency 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

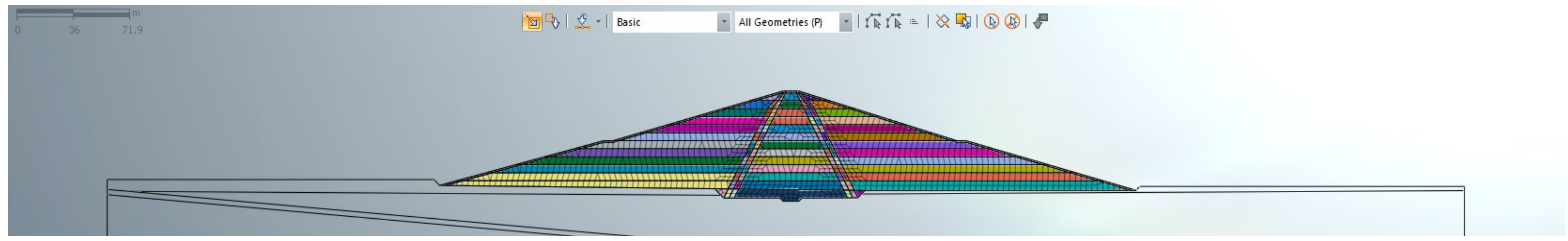
Modeling an Earthfill Dam with Construction Stages

1



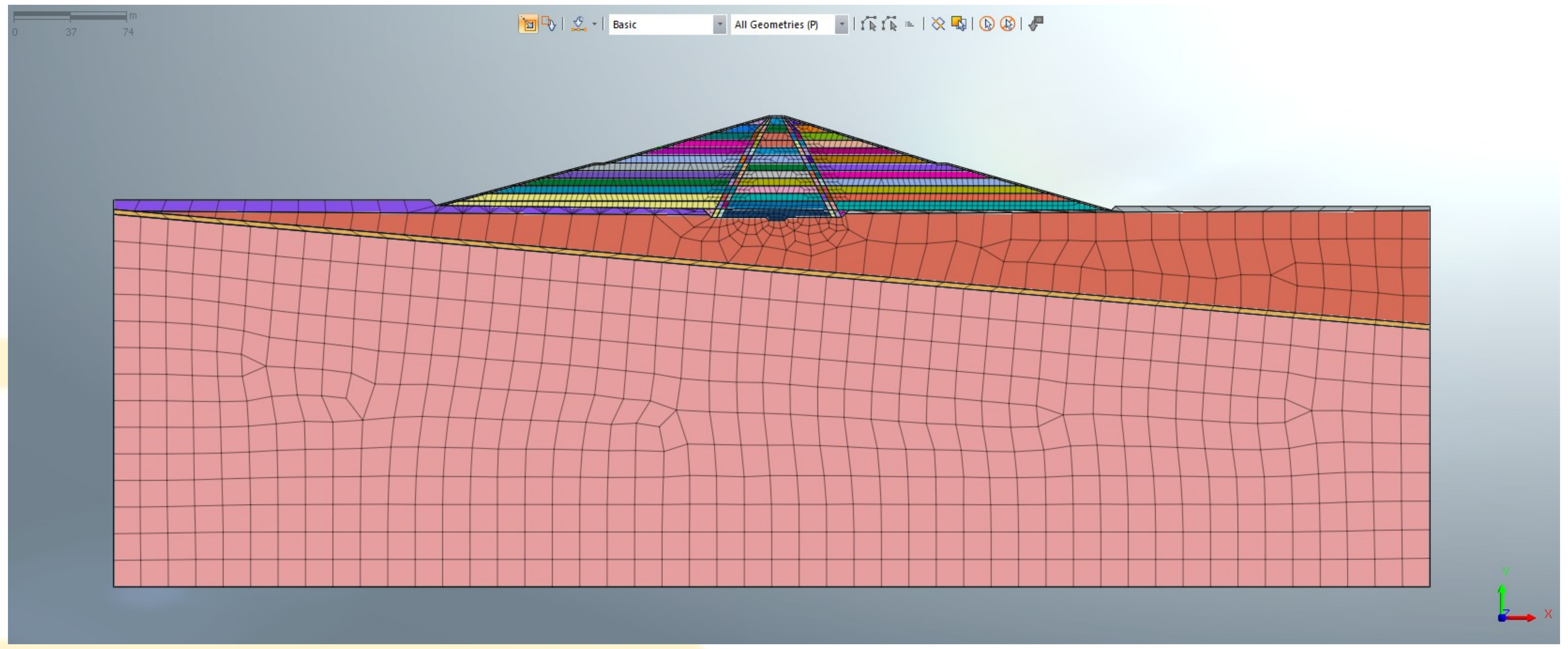
1) Importing a cross-section from .dxf file

2



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

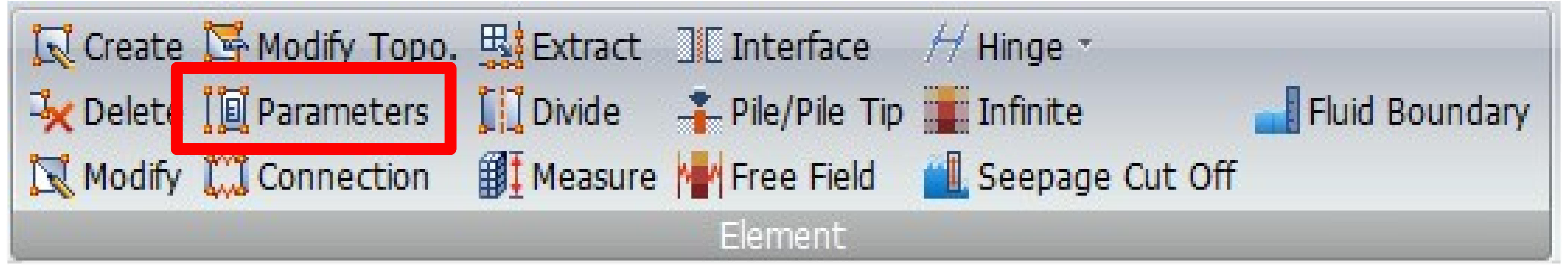
3



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

Useful Tools for Modeling

4



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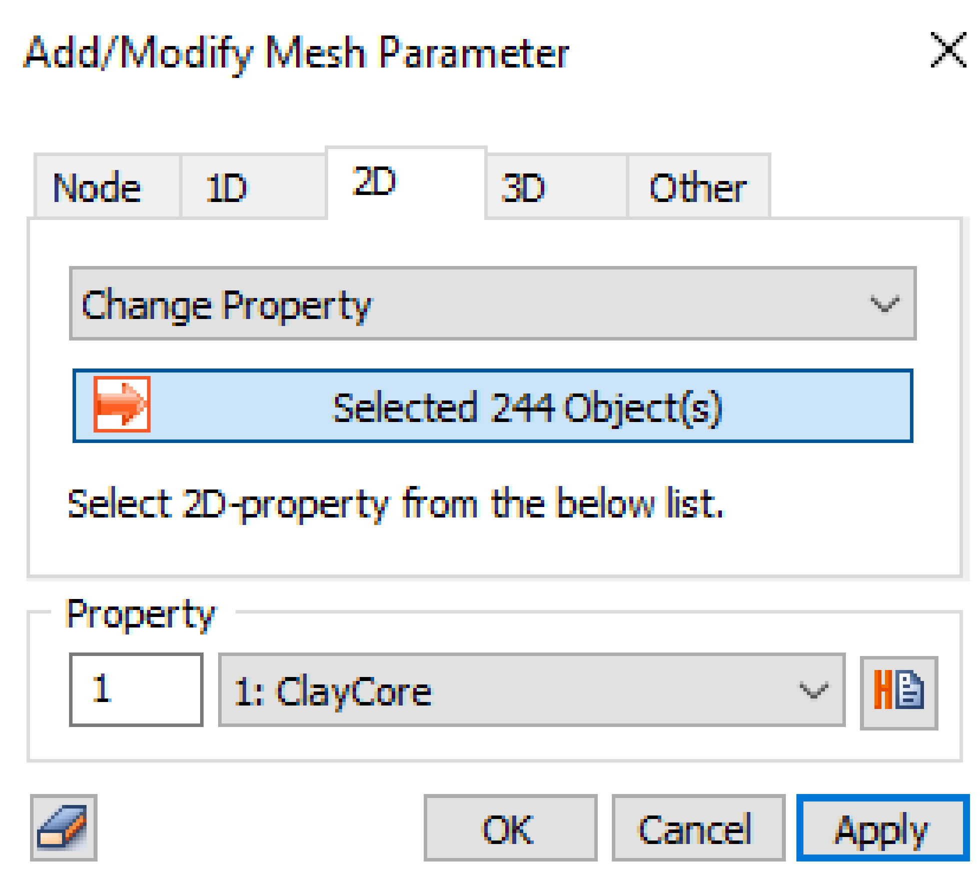
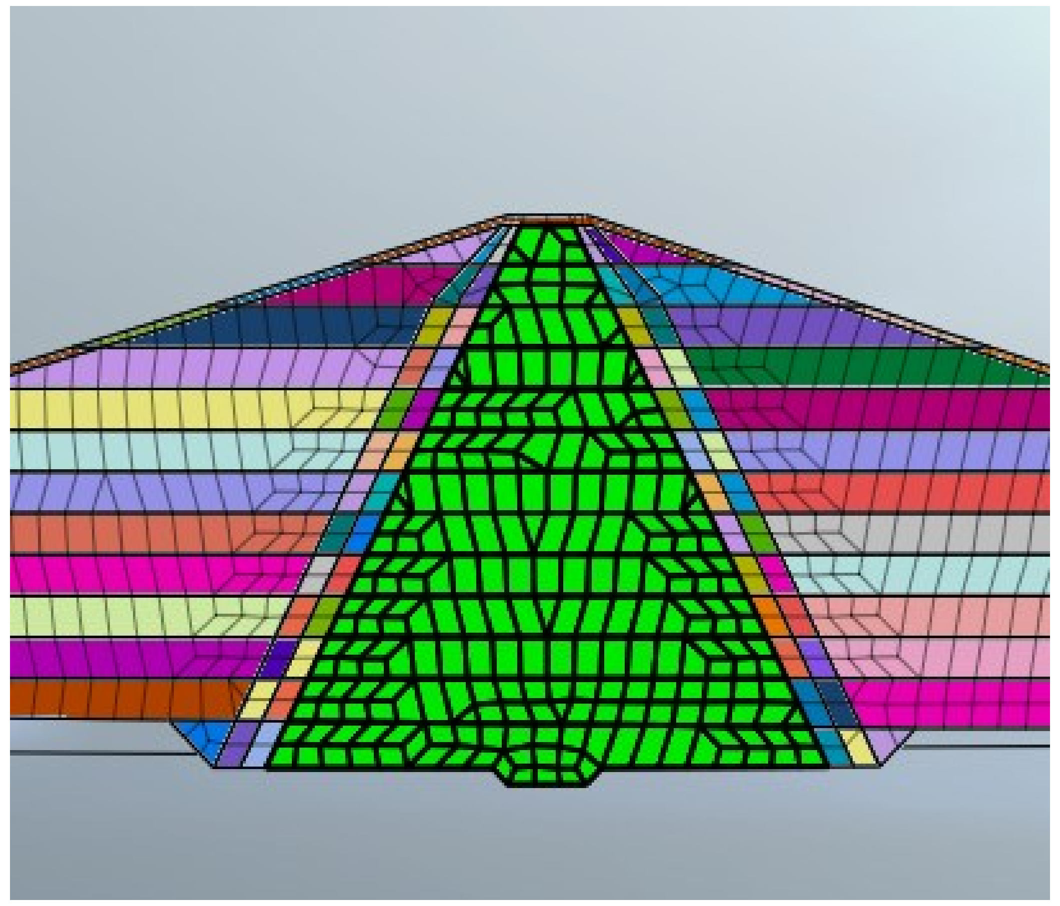
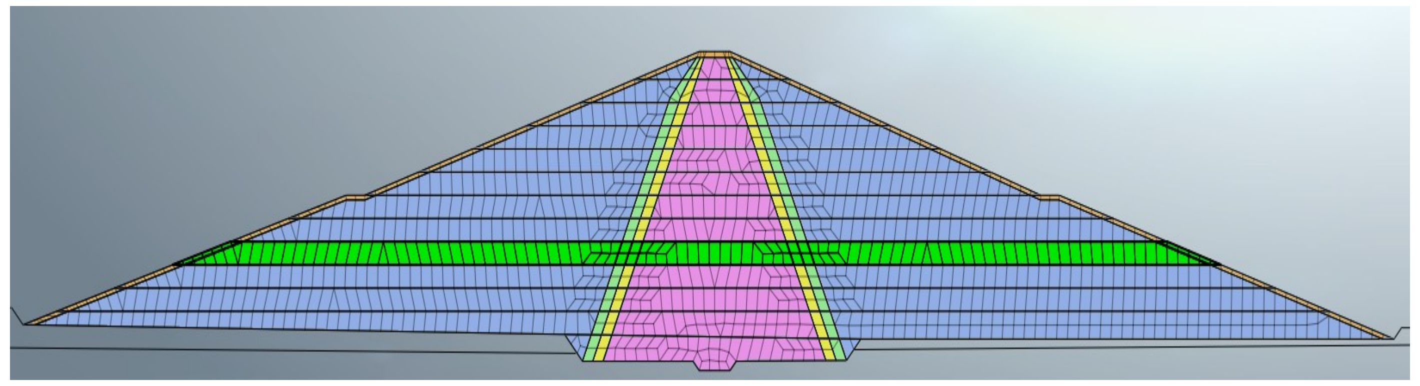


6

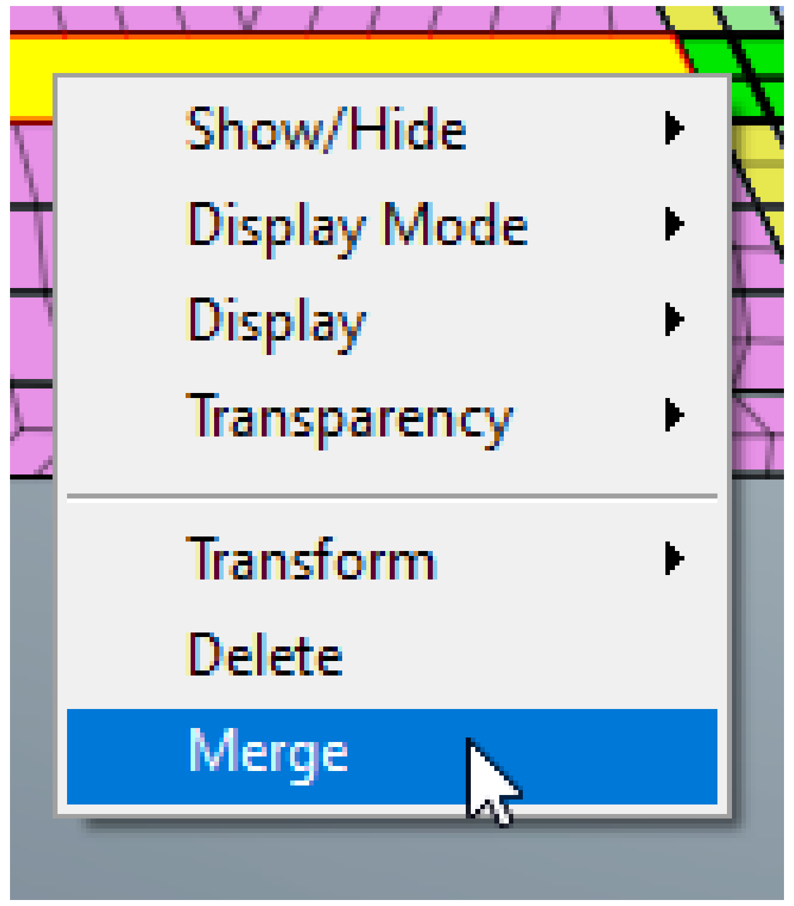


4,5,6) After fast meshing, define material properties to the mesh sets

7

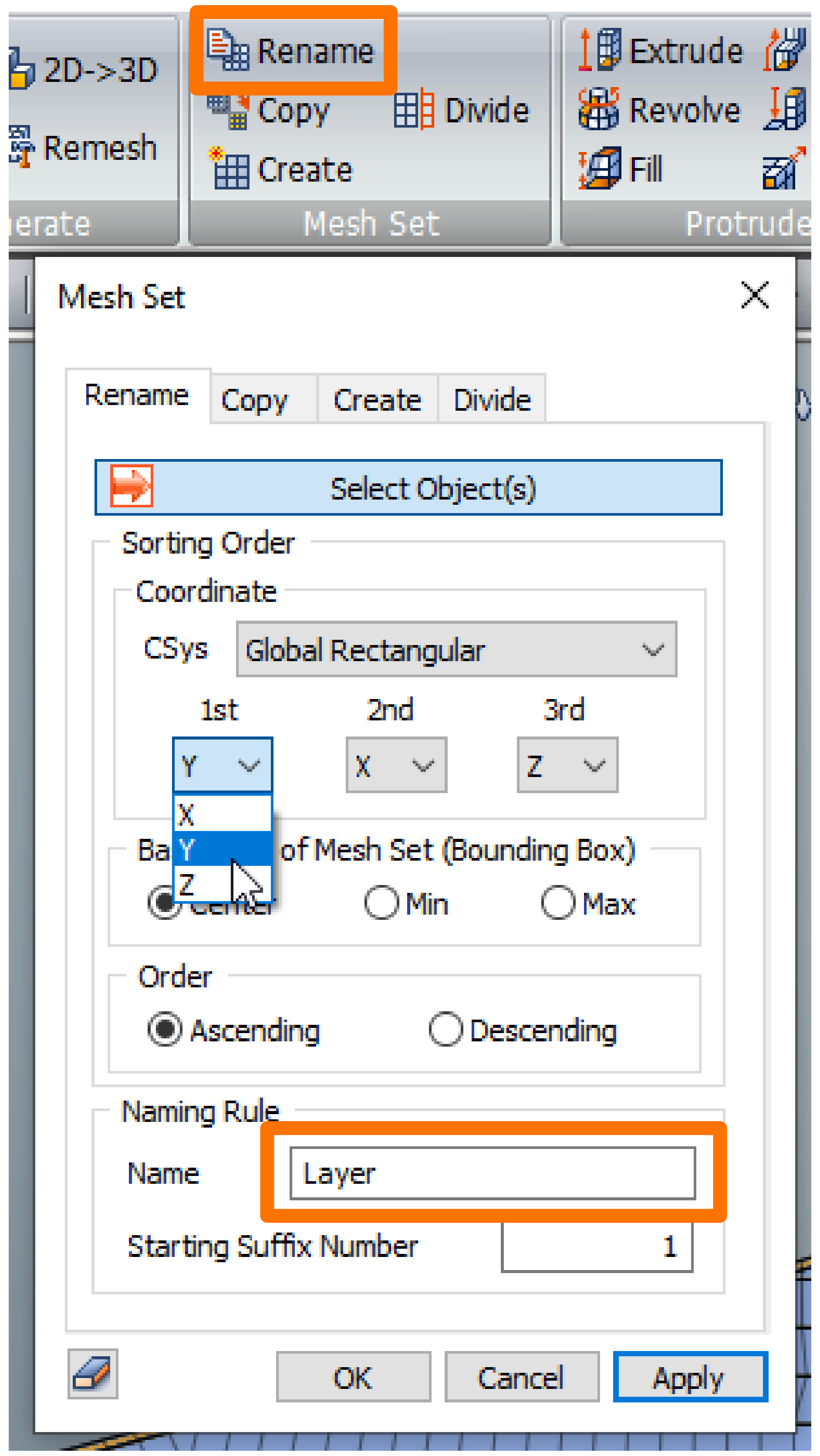


8



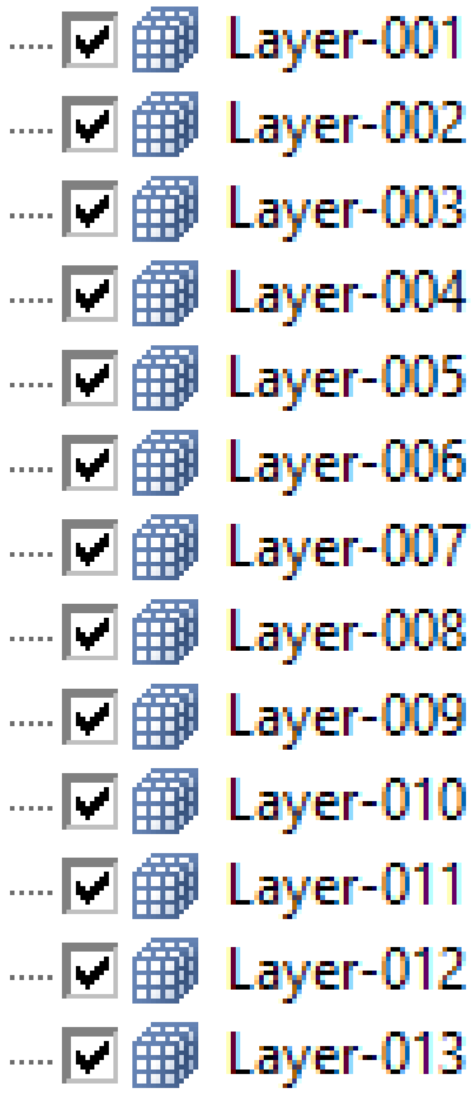
7,8) Select layers and merge

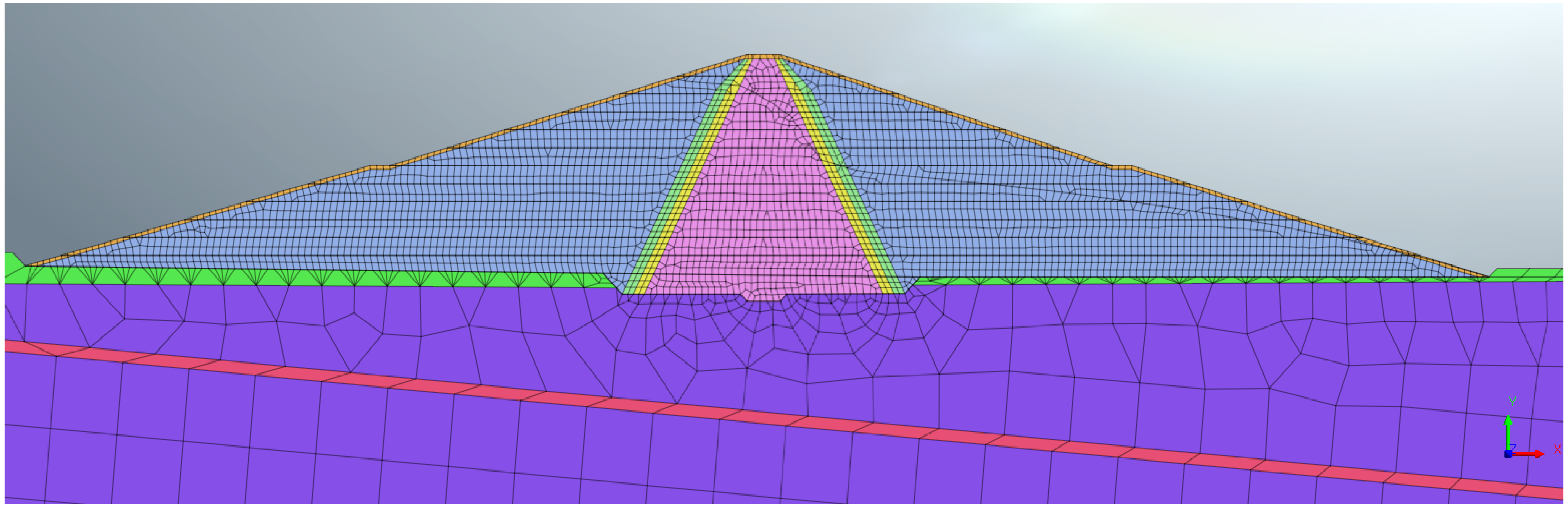
9



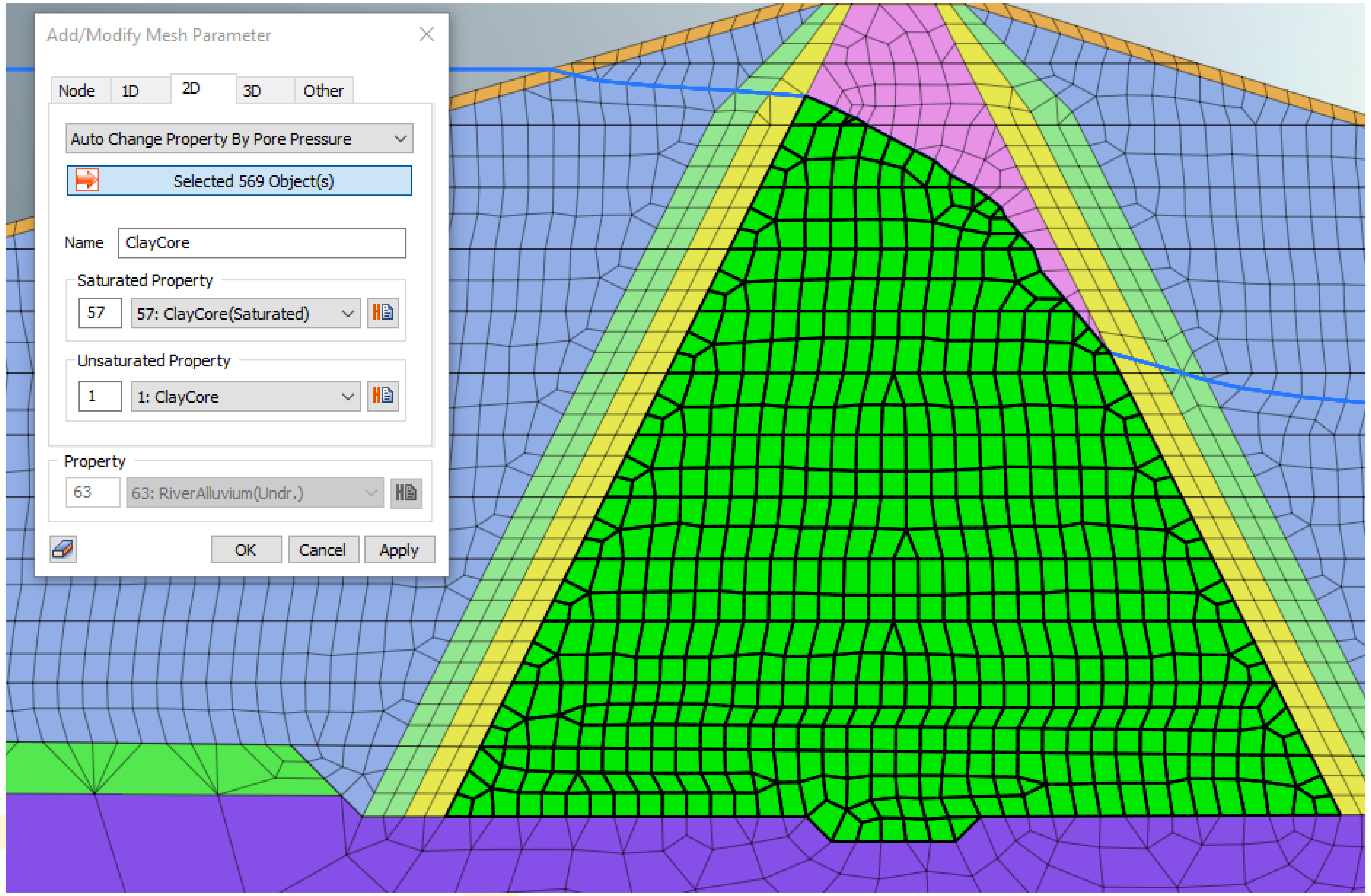
9) Select the layers and rename

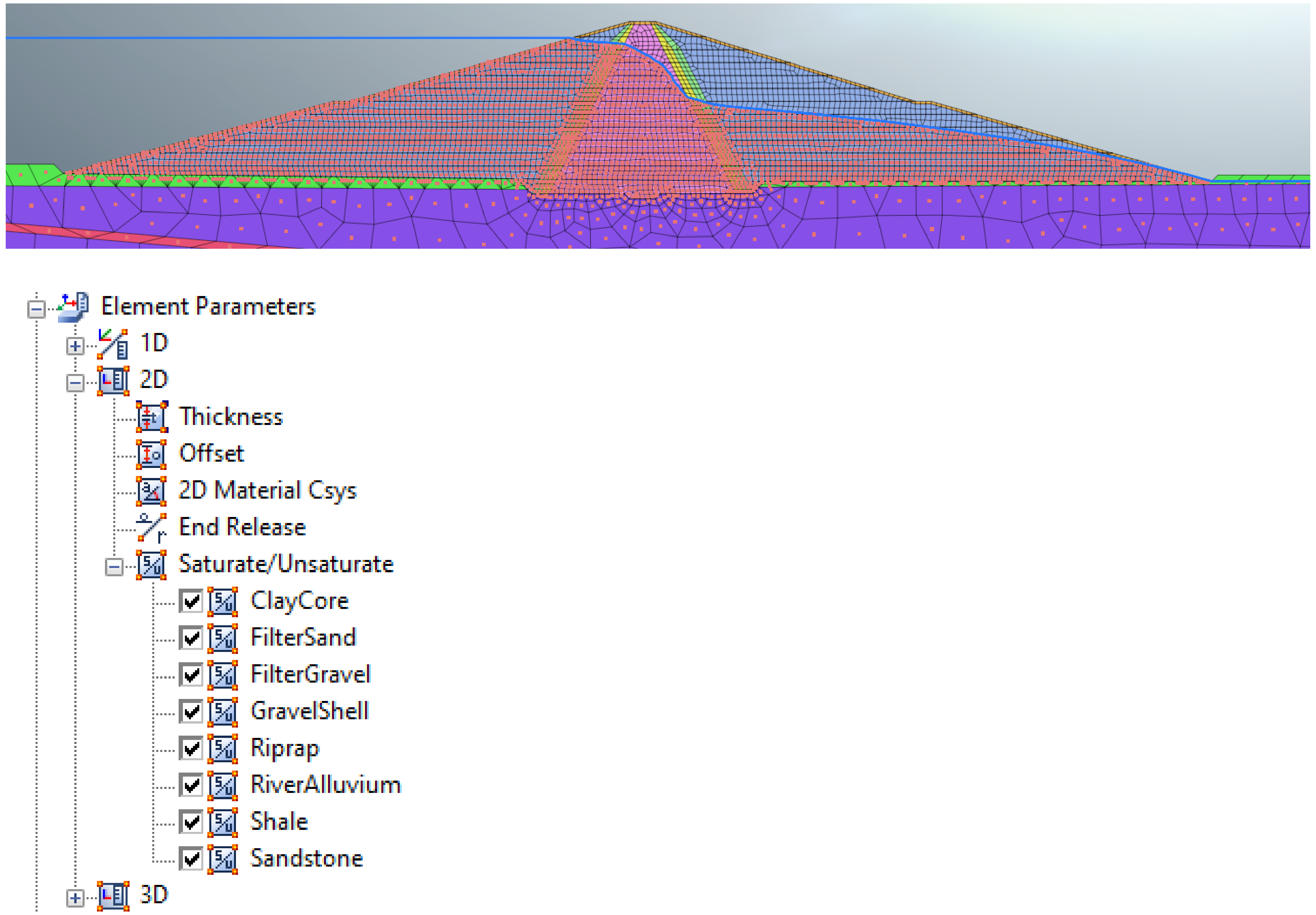
Layers are properly defined.



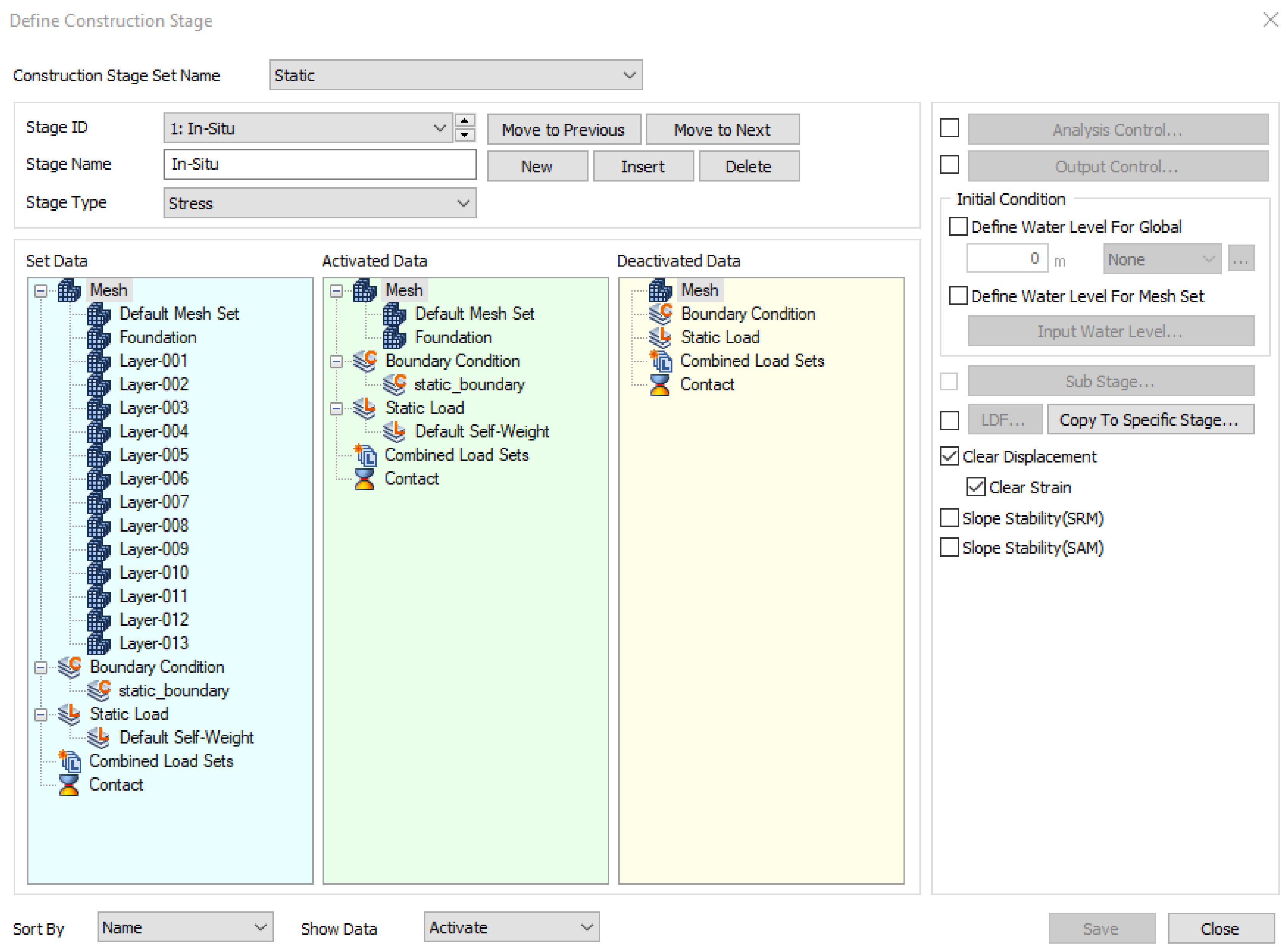


Auto Change of Saturated Material Parameters

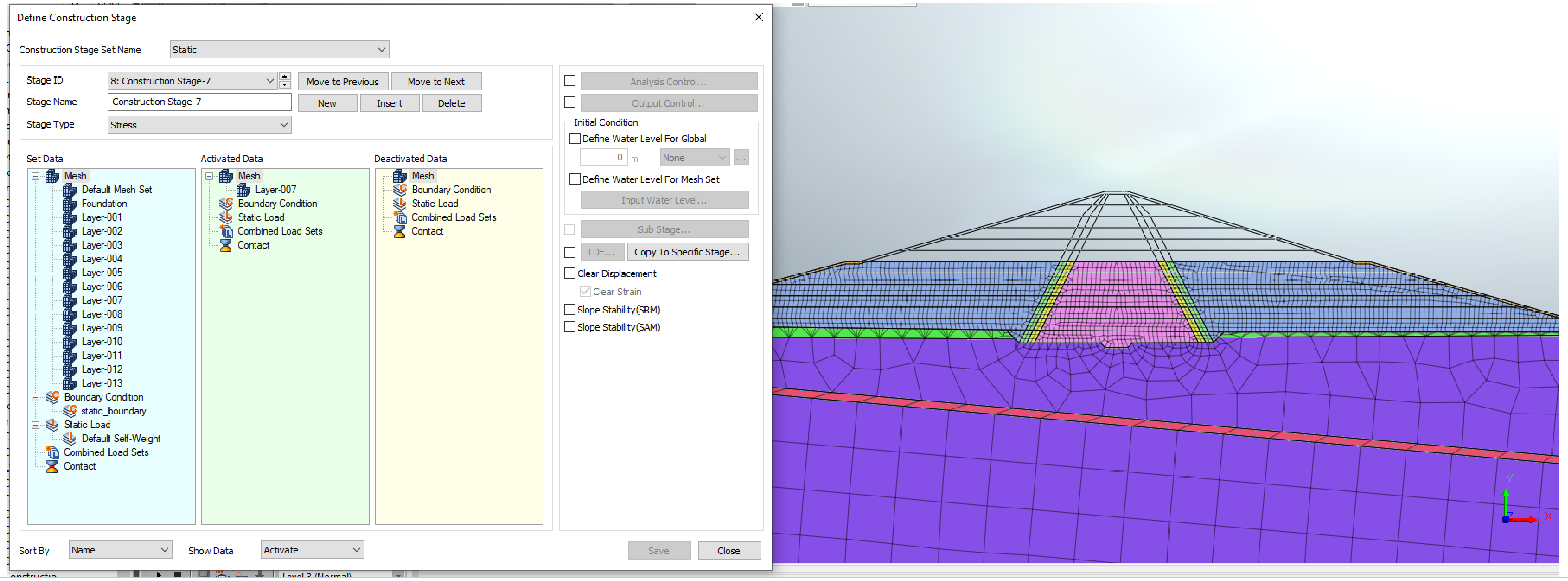




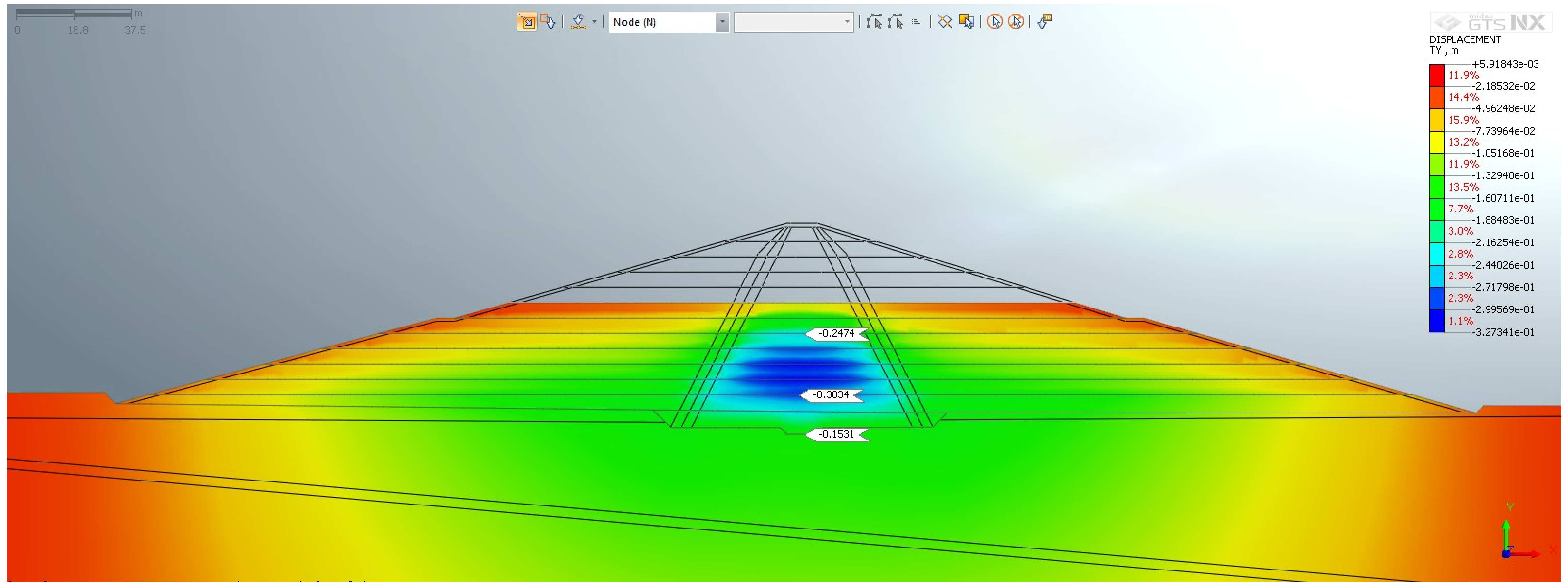
Auto Change of Saturated Material Parameters

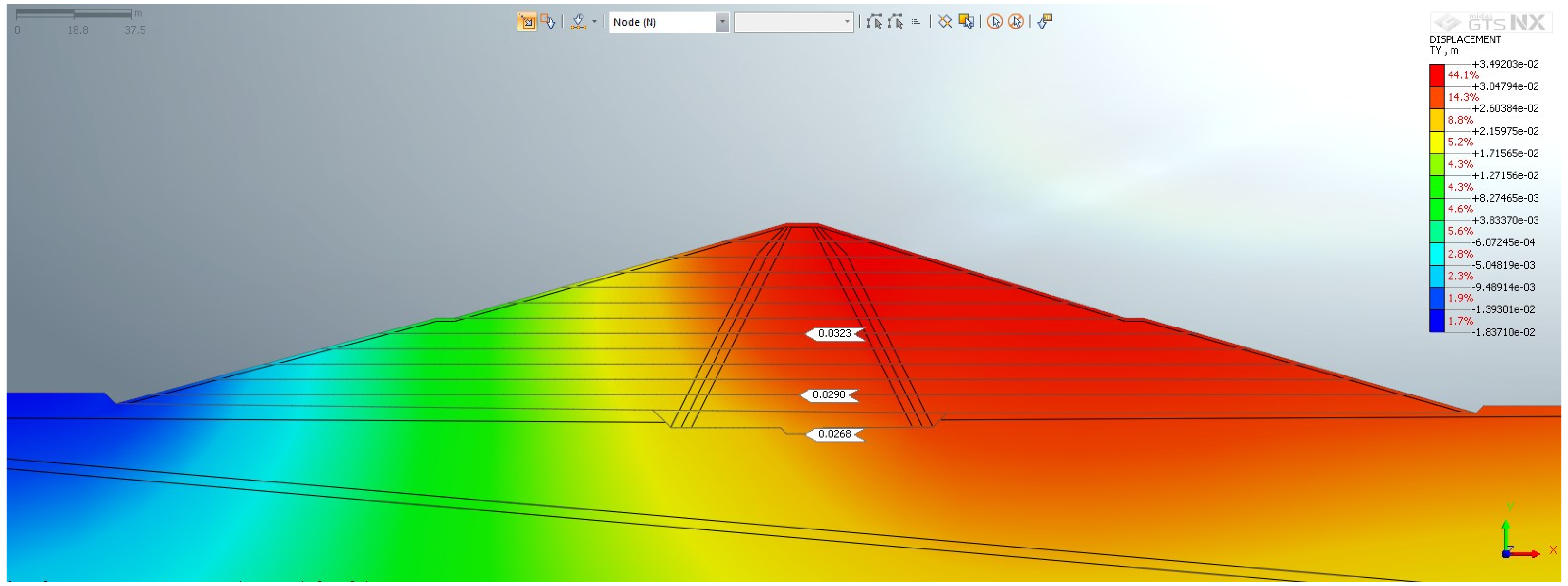


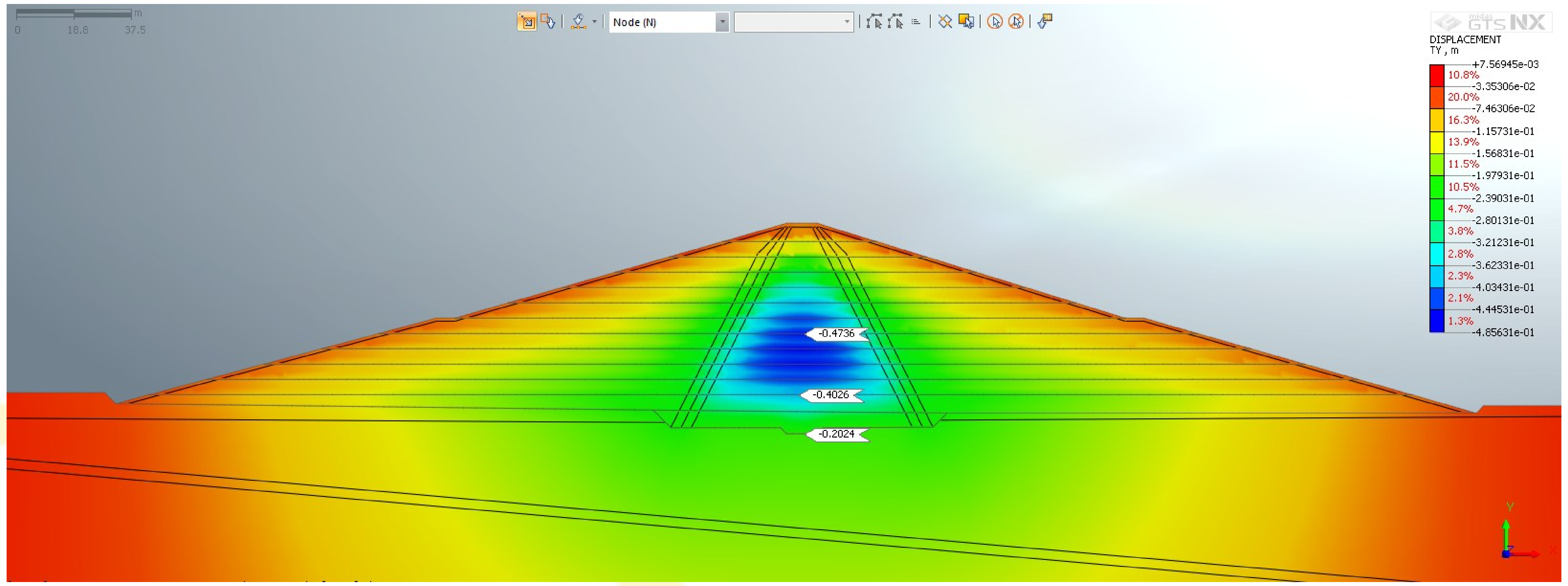
By adding the layers step by step, we define the construction stages



Results







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

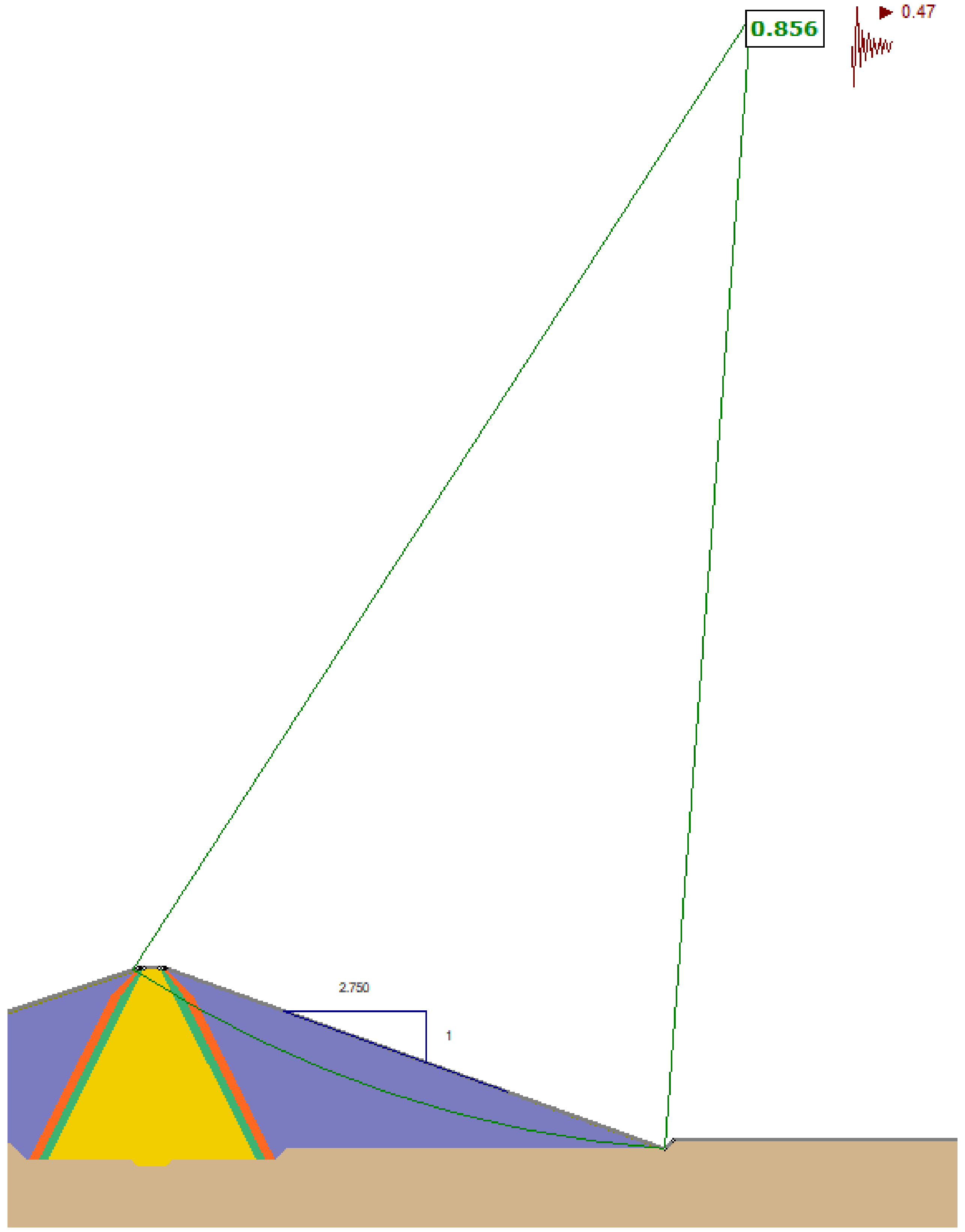
Challenges in Dynamic Stability

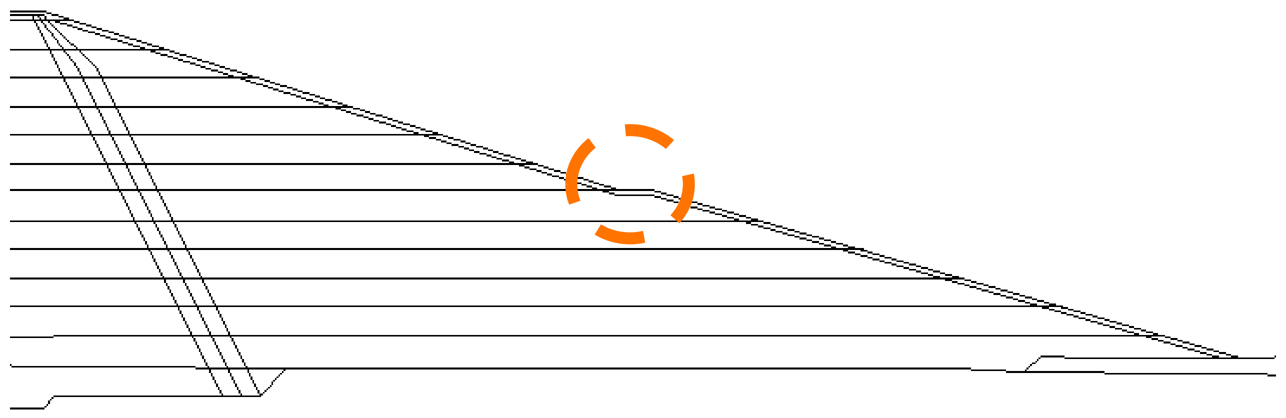
The project is in a seismically active zone. Recommended PGA value in Seismic Hazard Analysis Report was 0.7g.

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.

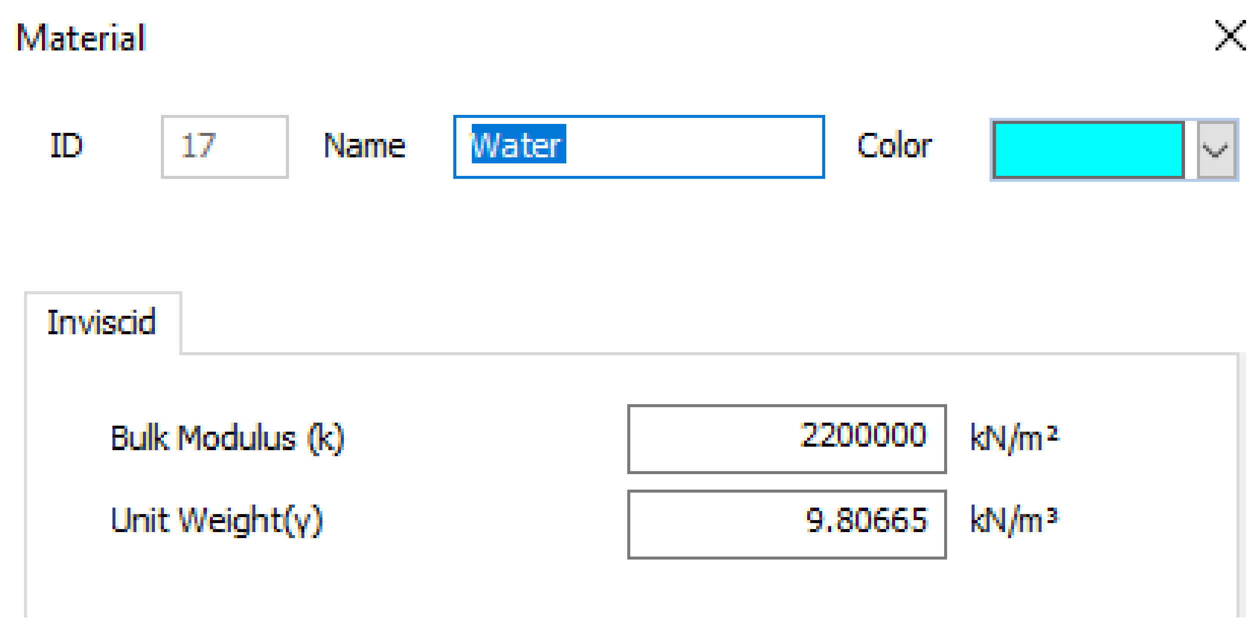
Static methods cannot capture oscillatory nature of earthquake ground motion, so dynamic analysis in a finite element software assess the seismic performance of the slopes better than limit-equilibrium methods.



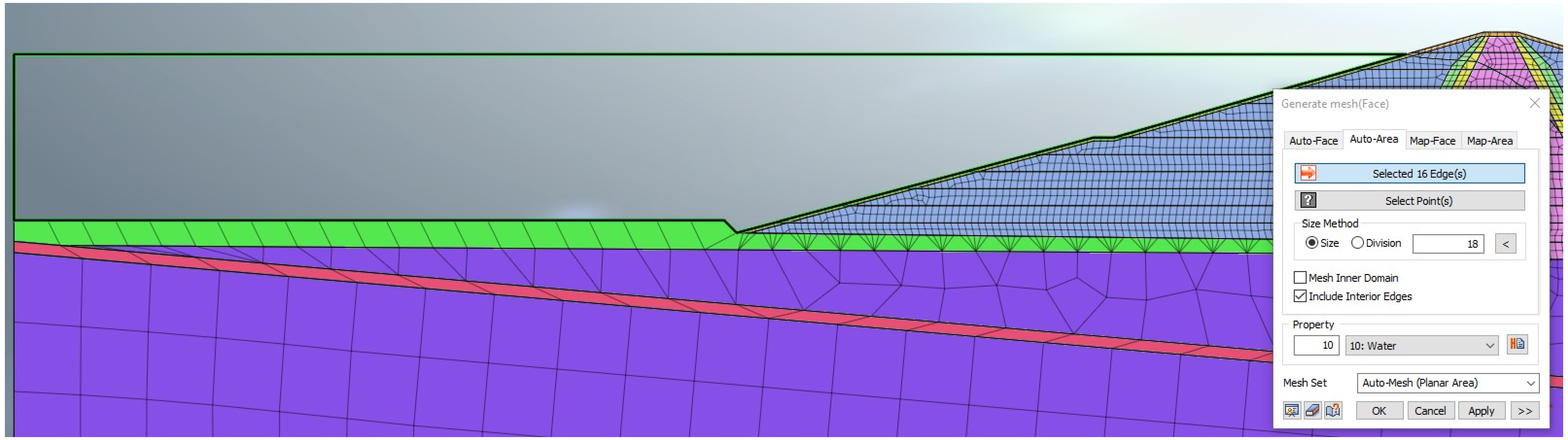


Dynamic Analysis

Sloshing Medium



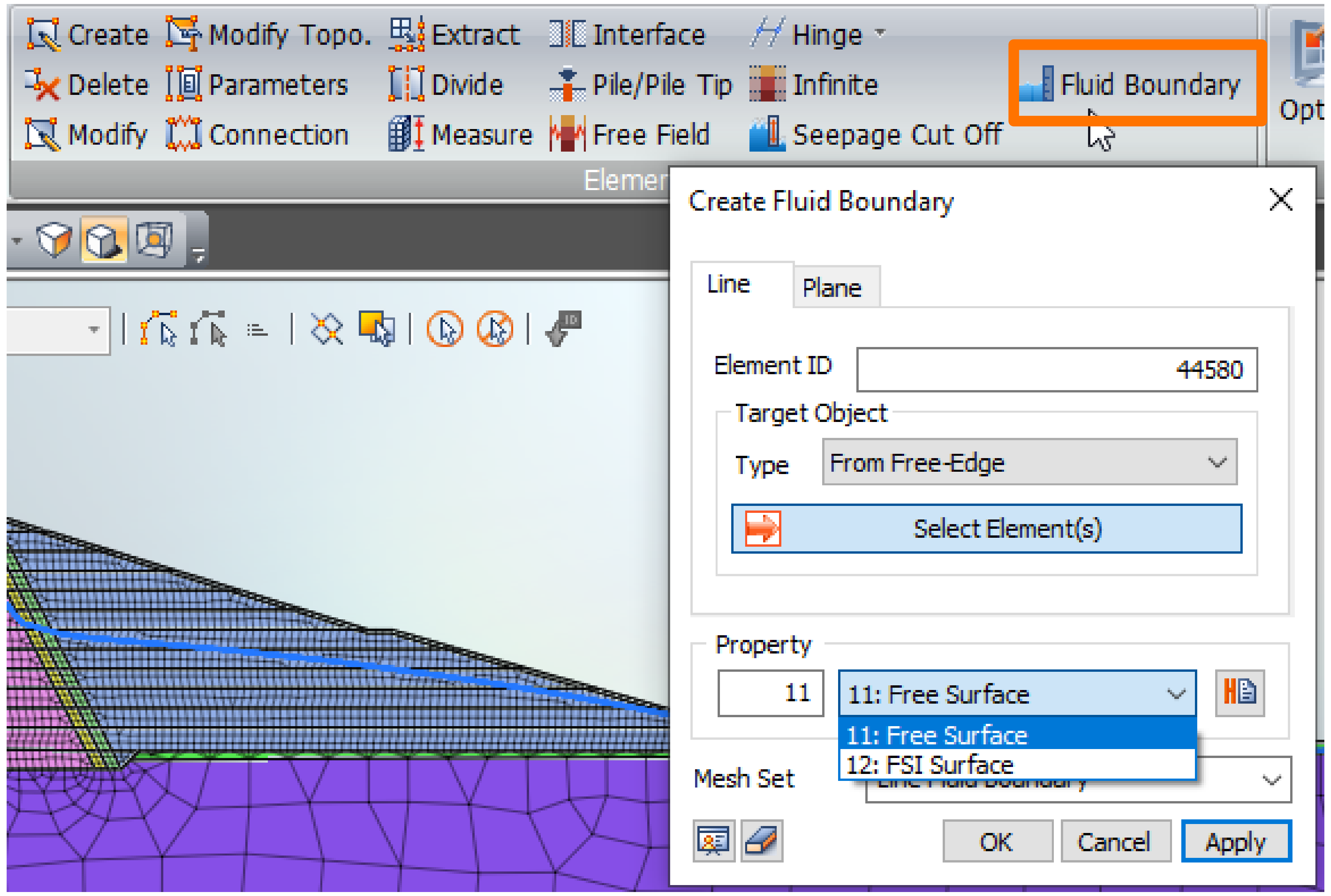
The water in the reservoir can be interpreted directly with a sloshing medium material and can be meshed easily as other materials.

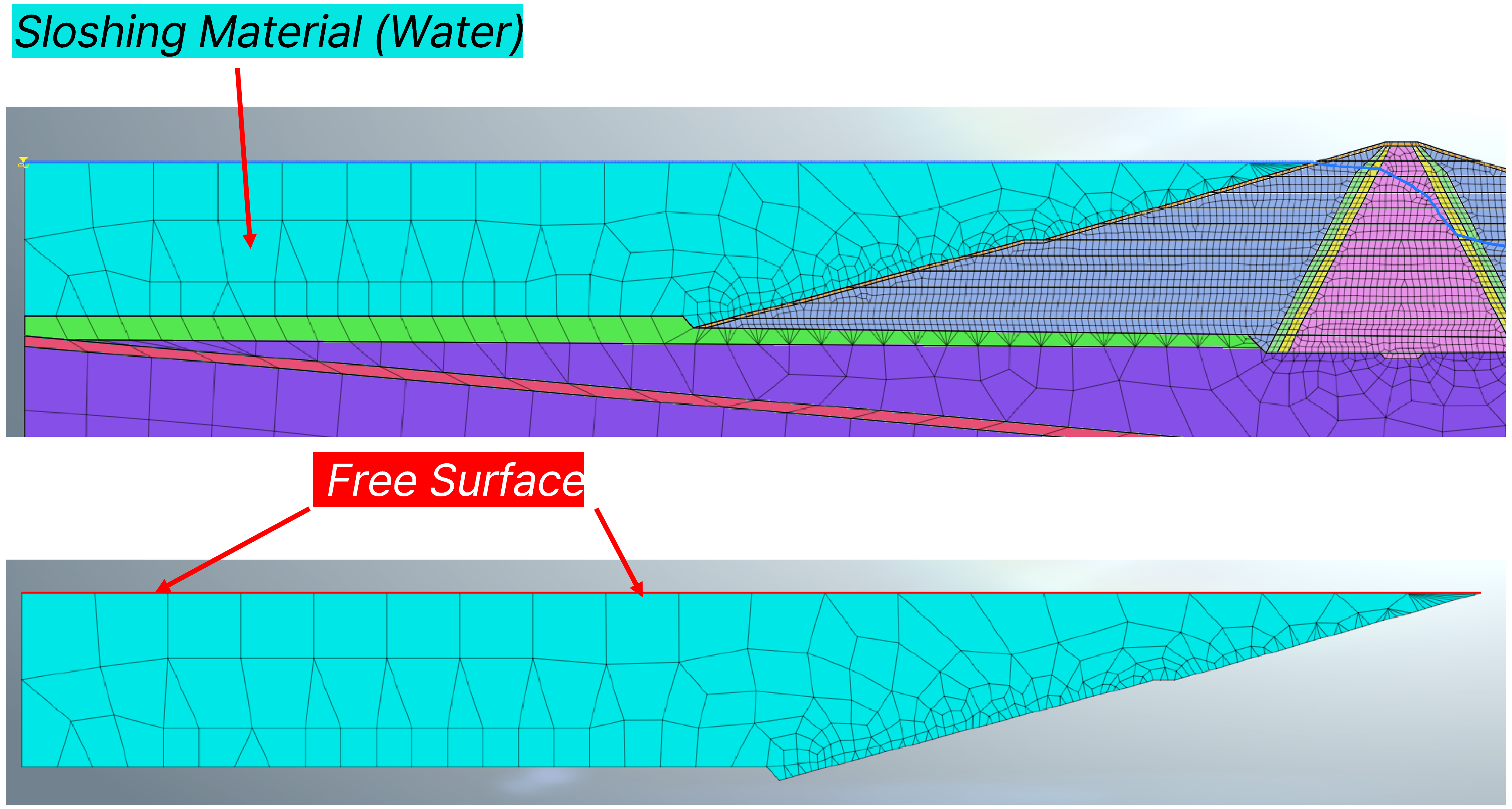


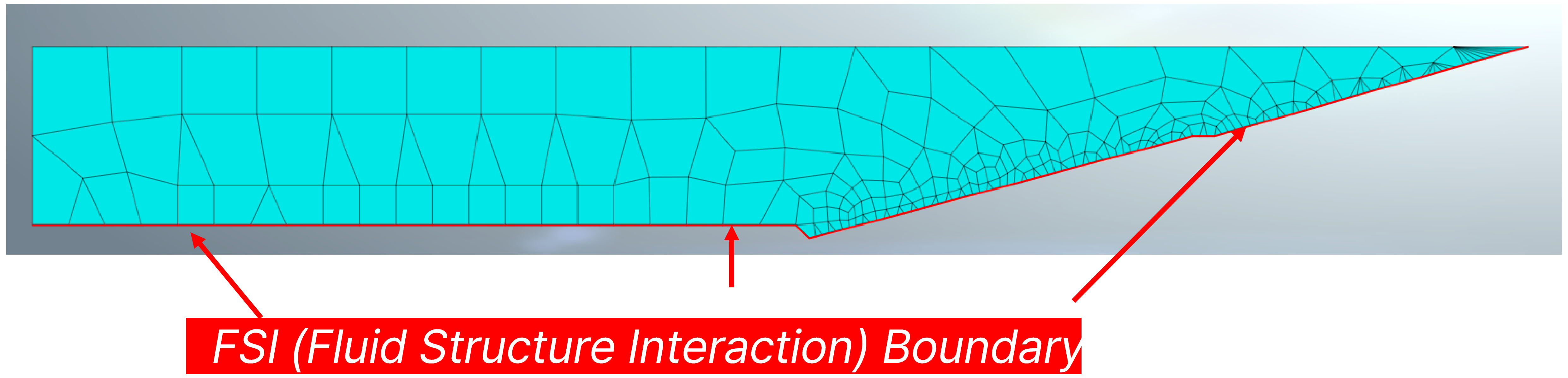
MIDAS

DOLSAR ENGINEERING

Sloshing Fluid Boundaries

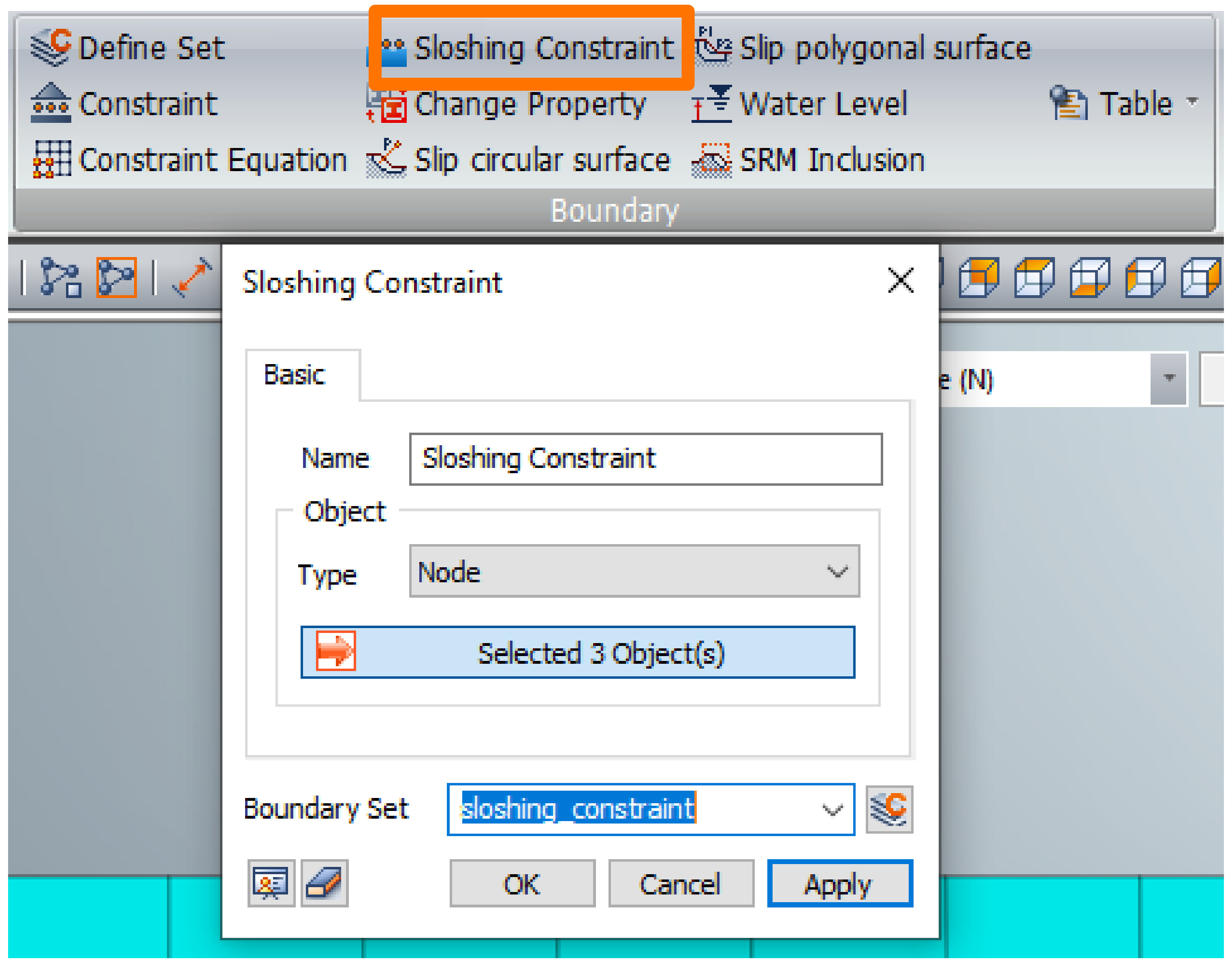


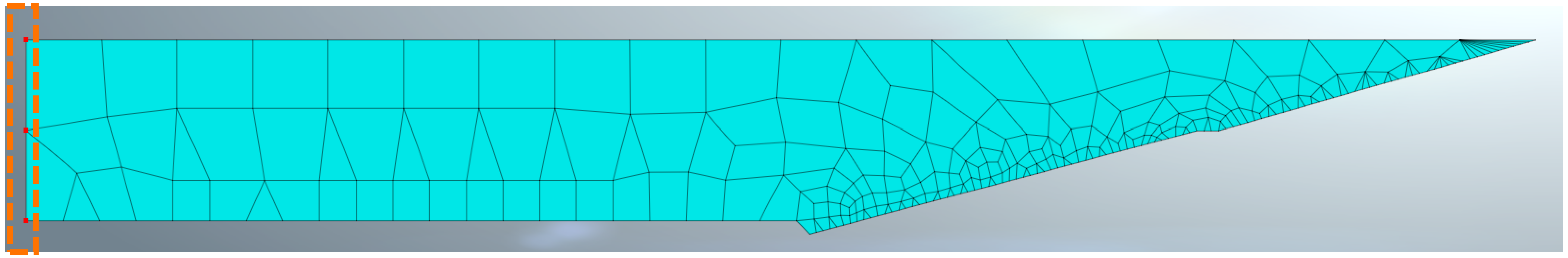




Do not forget to close other meshes while defining fluid boundaries!!

Sloshing Fluid Boundaries

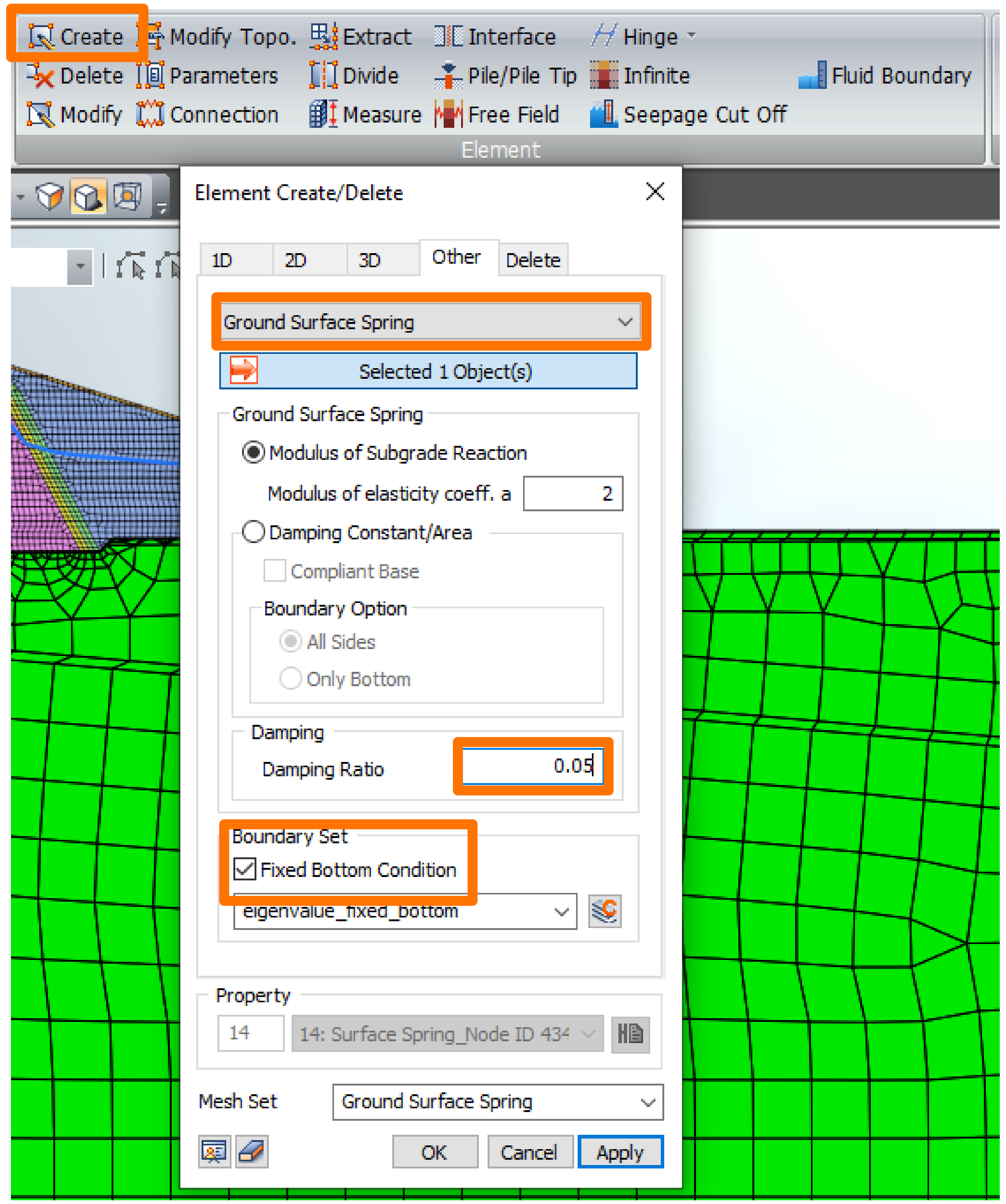




Sloshing constraint will simulate our long reservoir.

Eigenvalue Analysis

Boundary conditions for eigenvalue analysis



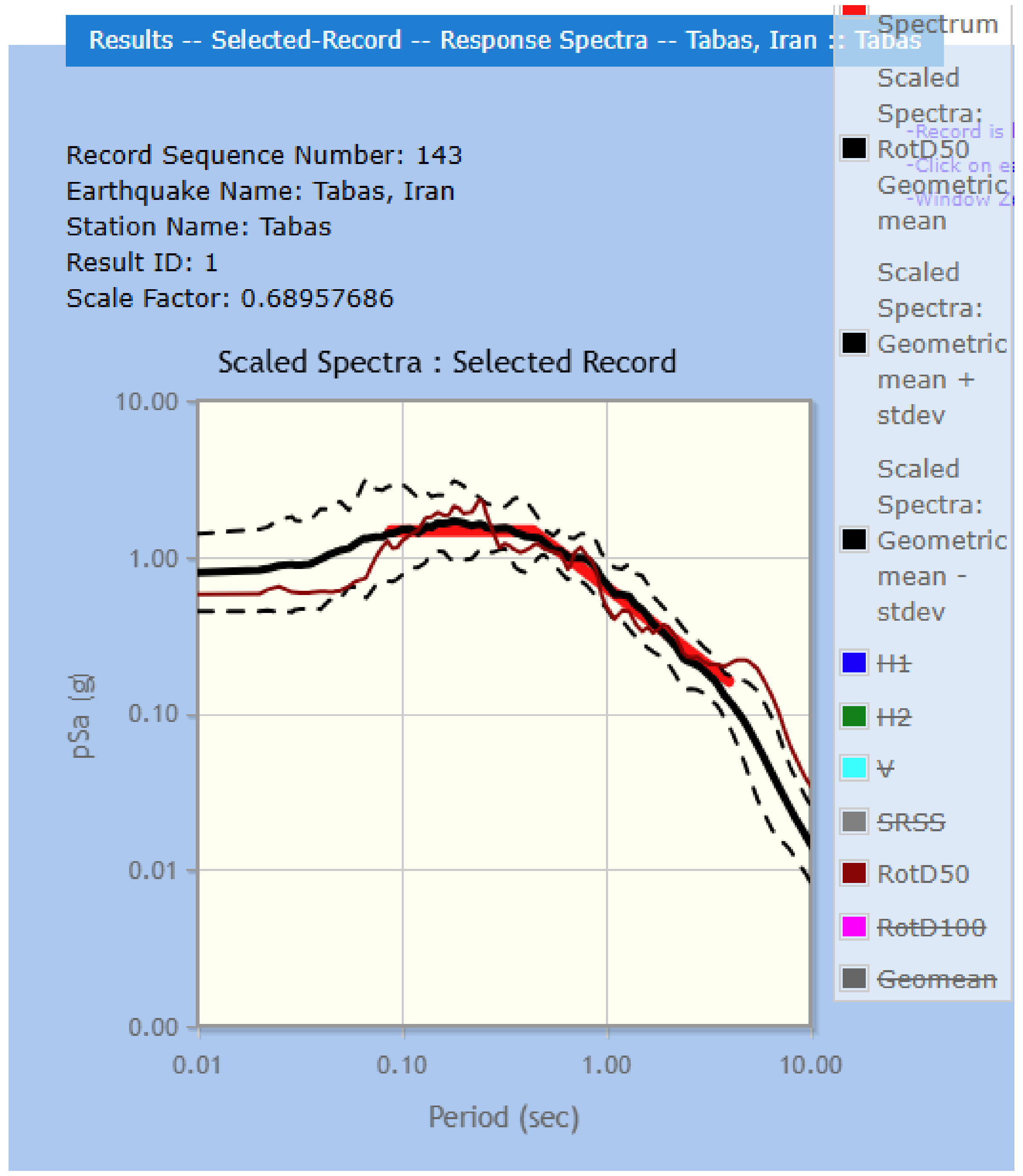
Eigenvalue Analysis

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	15.56%	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	PREIOD	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	1.952566e+00	1.397343e+00	2.223940e-01	4.496525e+00	1.000000e+00	1.952566e+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	1.544530e+00	2.458196e-01	4.068024e+00	1.000000e+00	2.385573e+00	2.326833e-12	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



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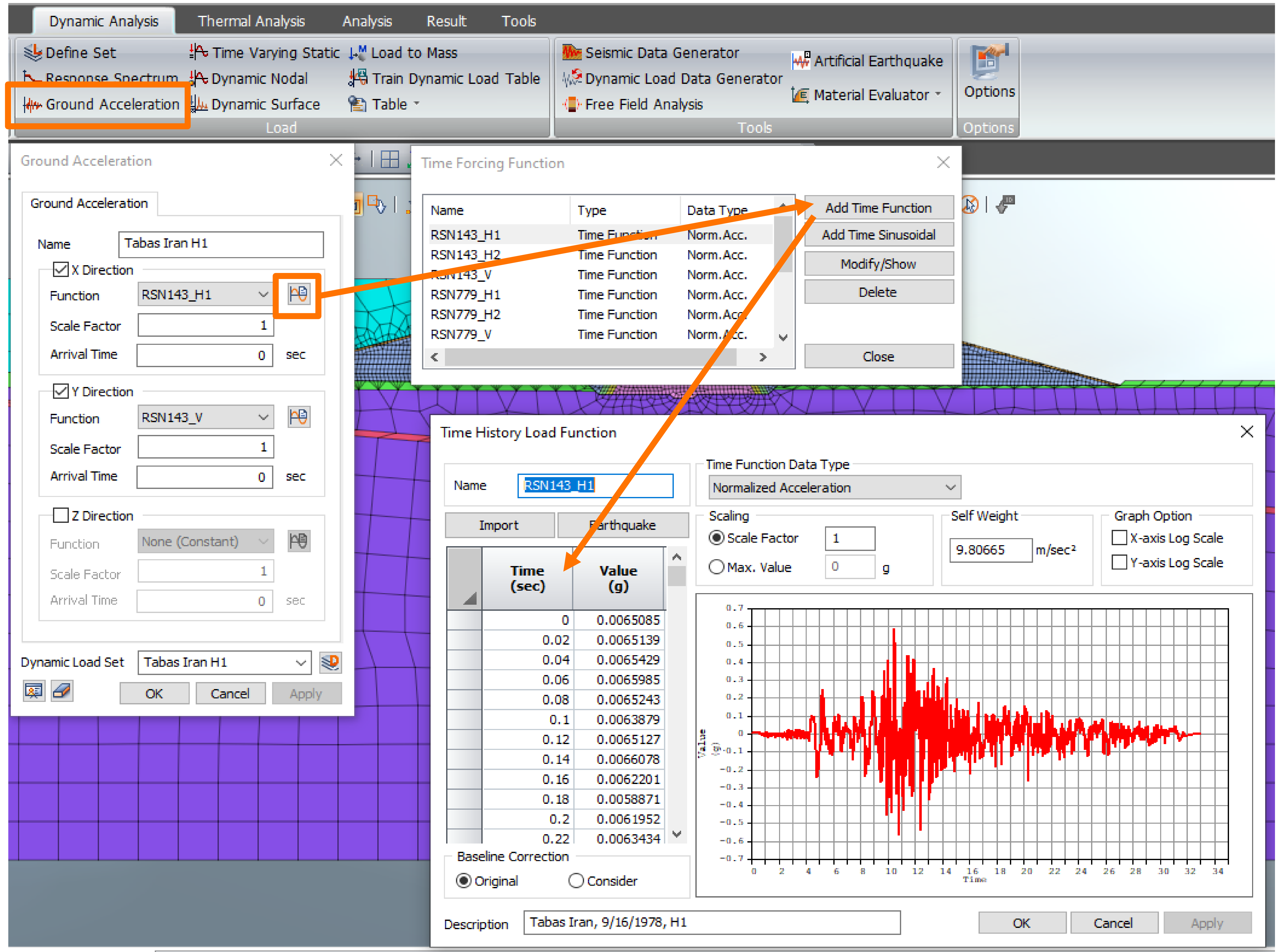


[Dynamic Analysis]

> [Ground Acceleration]

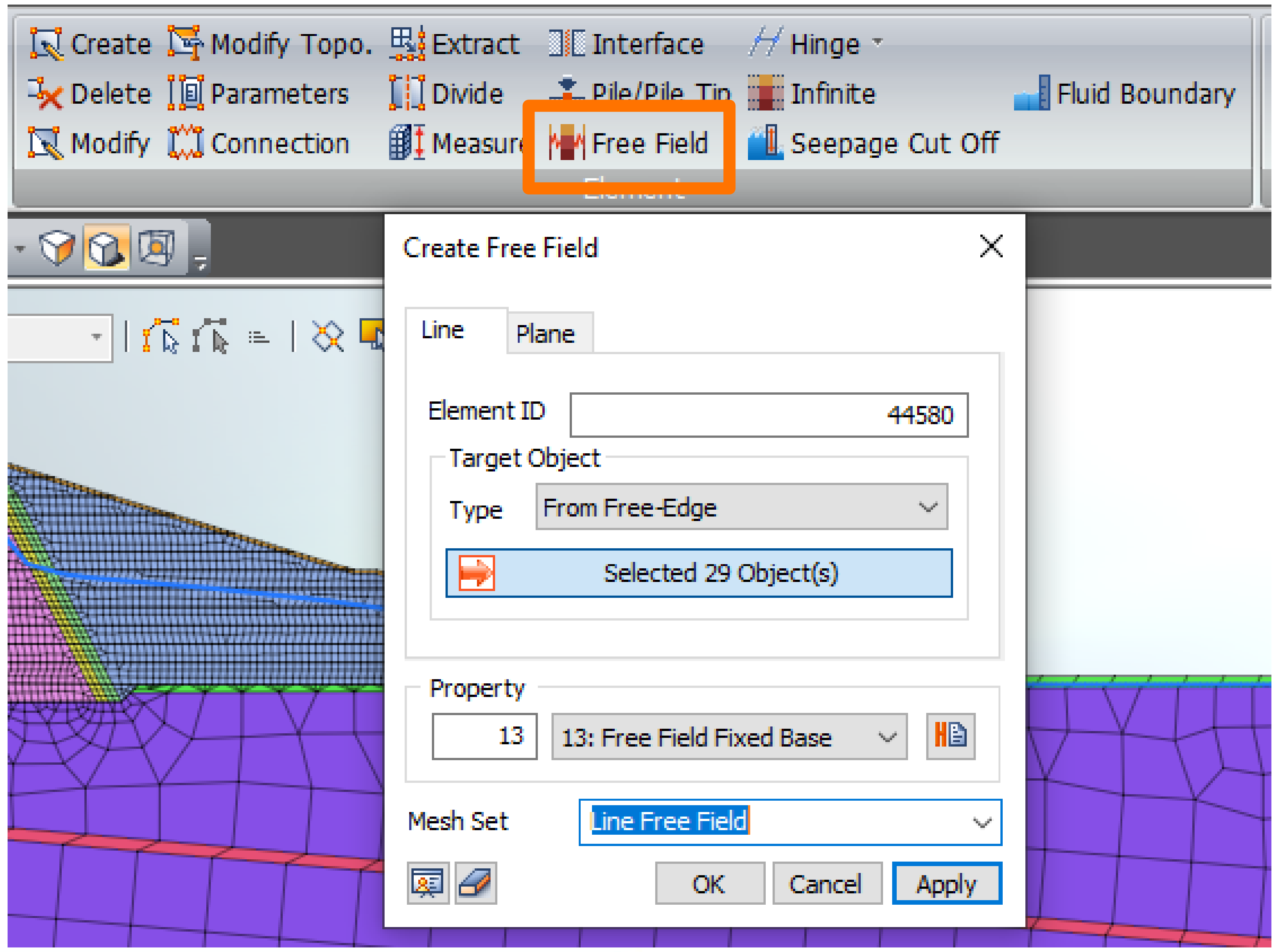
> [Time Forcing Function]

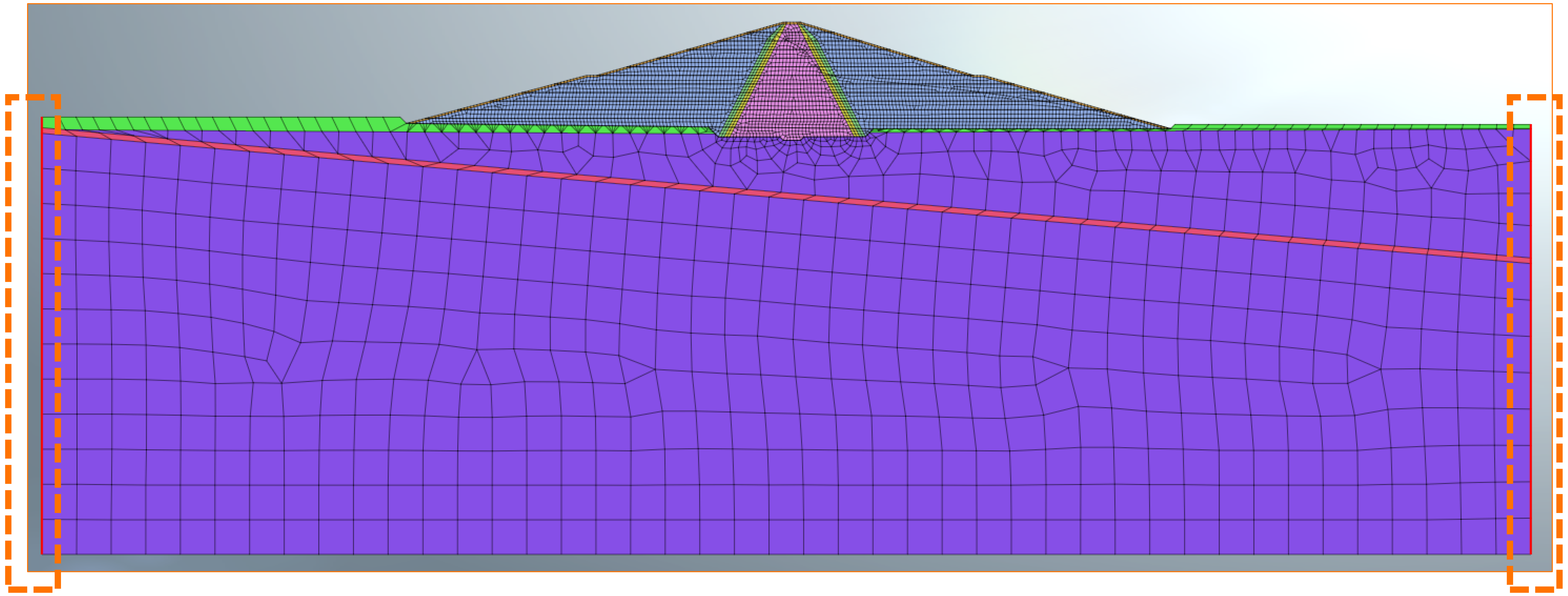
> [Add Time Function]

and copy/paste the selected acceleration-time history recording.

Boundary Conditions for Dynamic Analysis

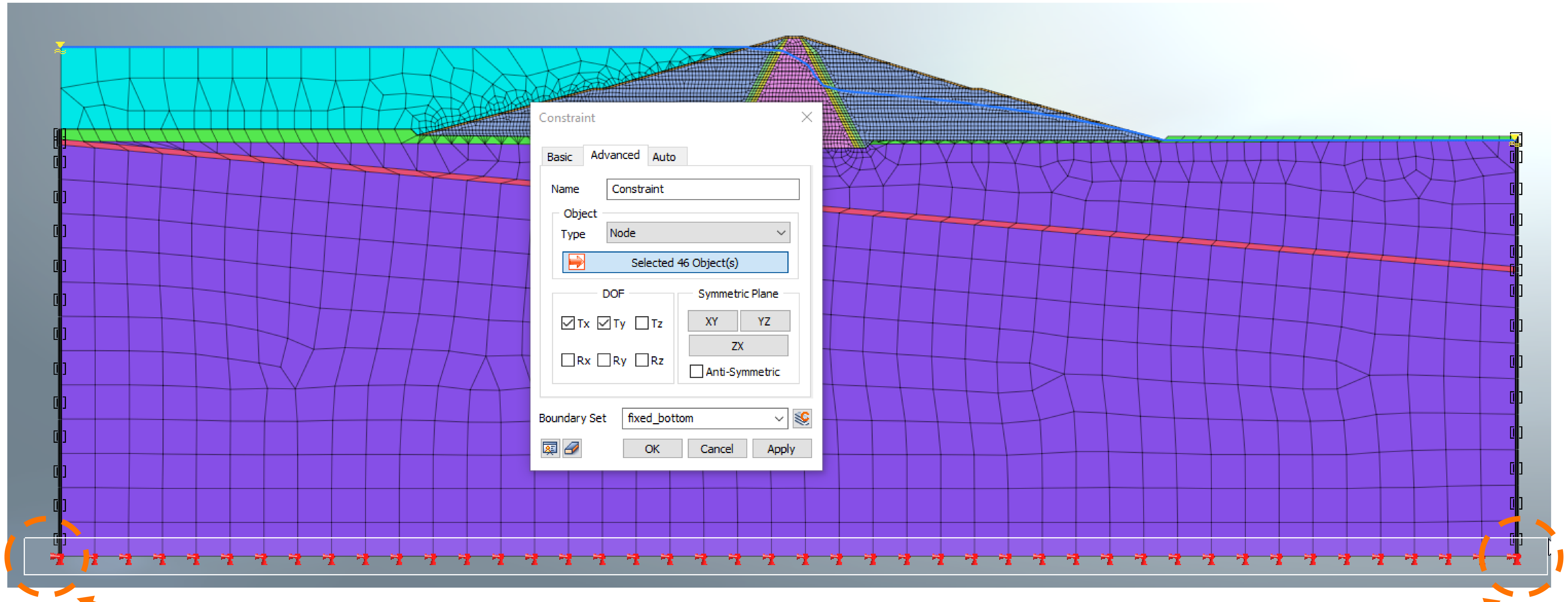
Free field conditions should be applied to the sides to simulate the infinite ground.





Boundary Conditions for Dynamic Analysis

Fixed boundary conditions for bottom are used for this analysis.

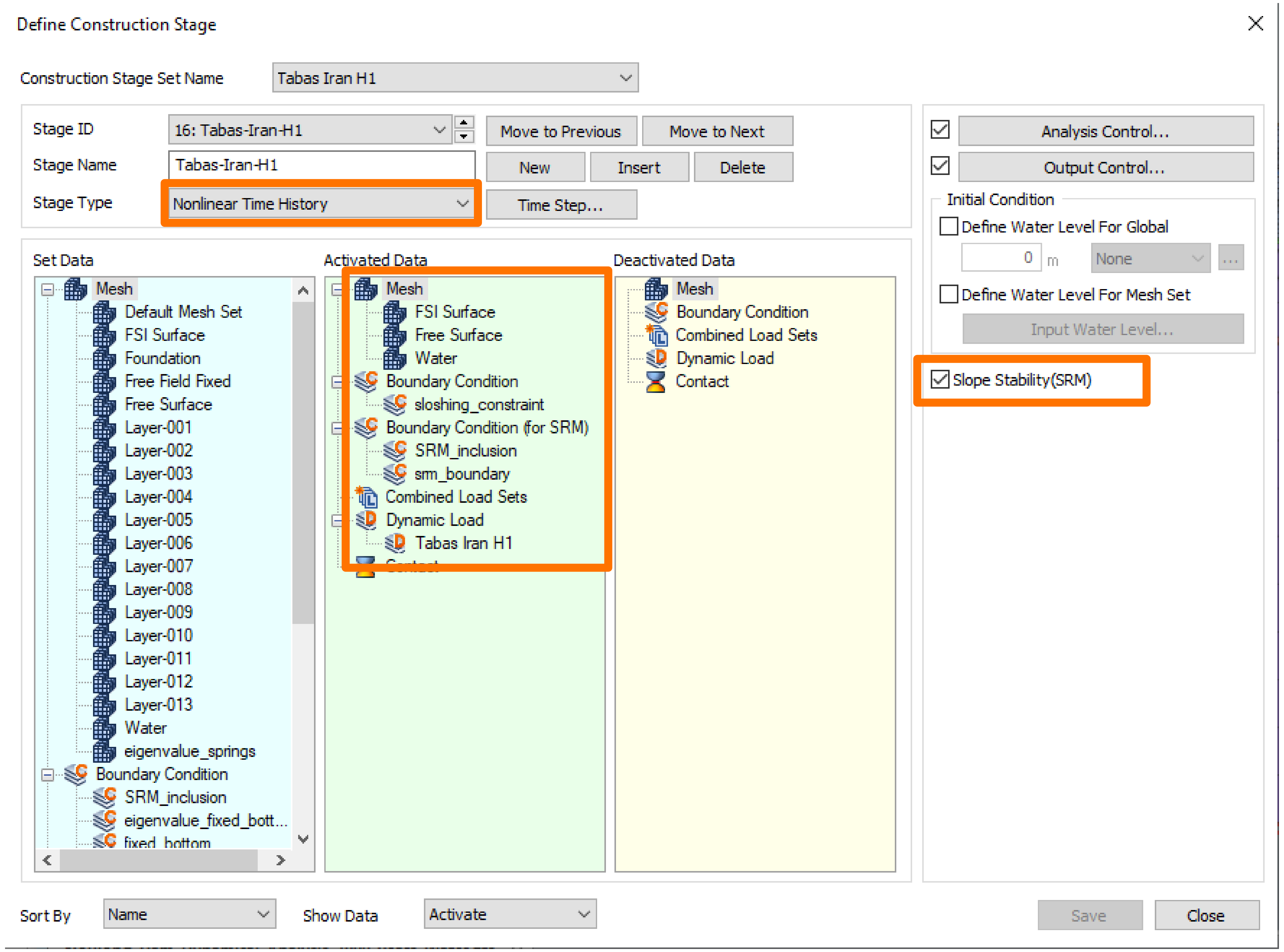


Caution: Bottom node of free field elements have to be fixed!

Preparation of Dynamic Step of Construction Stages

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

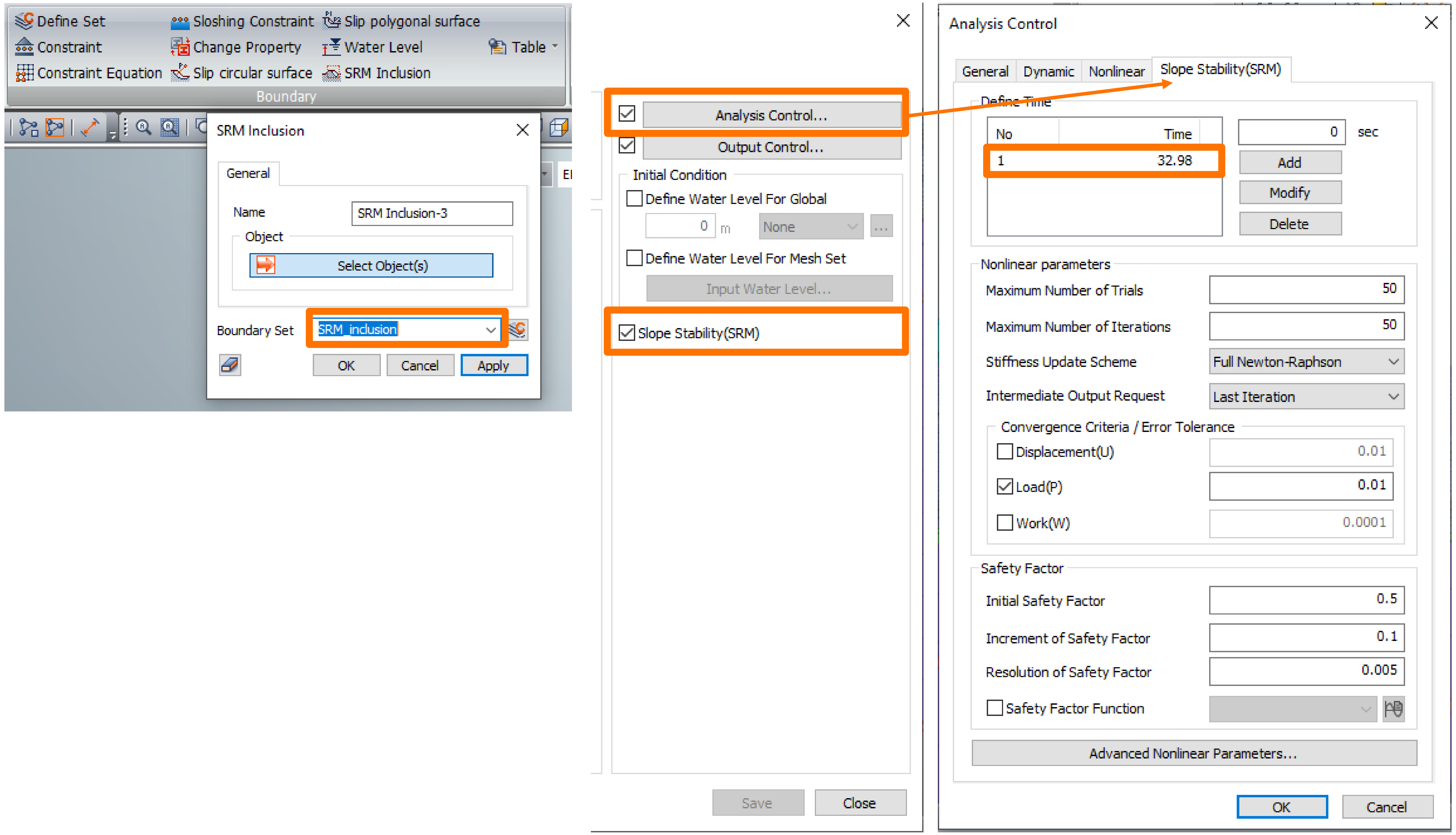
Here we add additional mesh sets and boundary conditions for sloshing material and SRM for post-earthquake slope stability check.



Defining SRM Inclusion & Post-Earthquake SRM Analysis

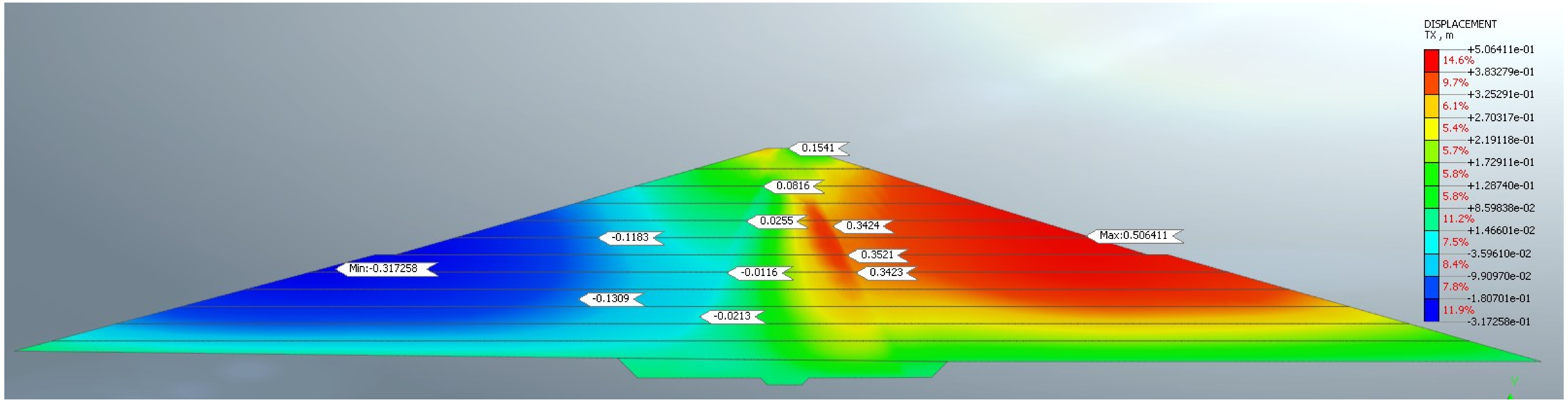
After SRM Inclusion zone has been defined; SRM tick in the dynamic construction stage analysis options should be activated.

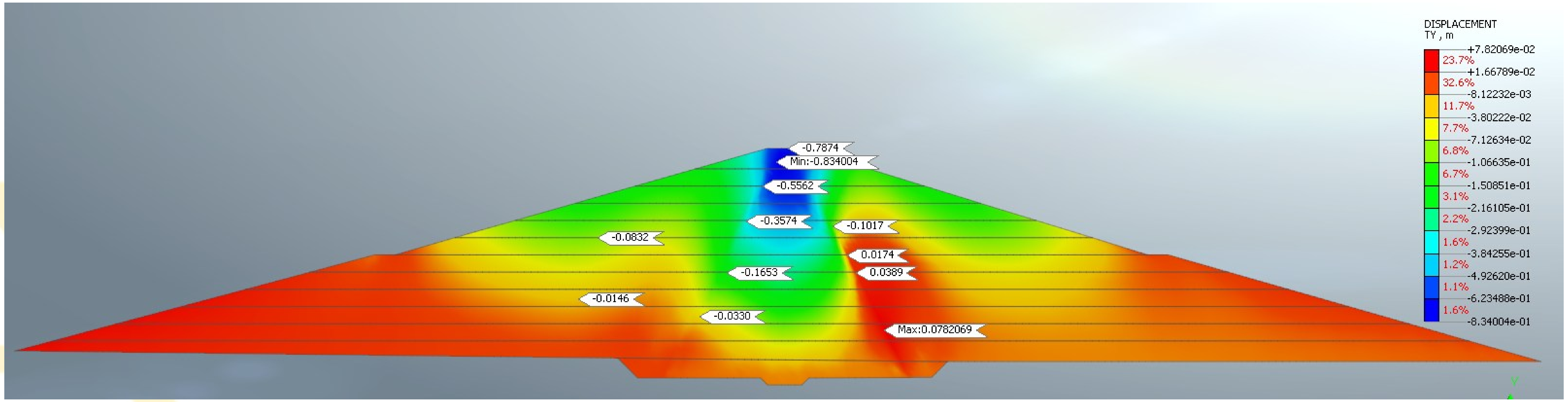
Later on, in analysis control the latest second of the acceleration-time history should be written to check slope stability with post-earthquake stresses.



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

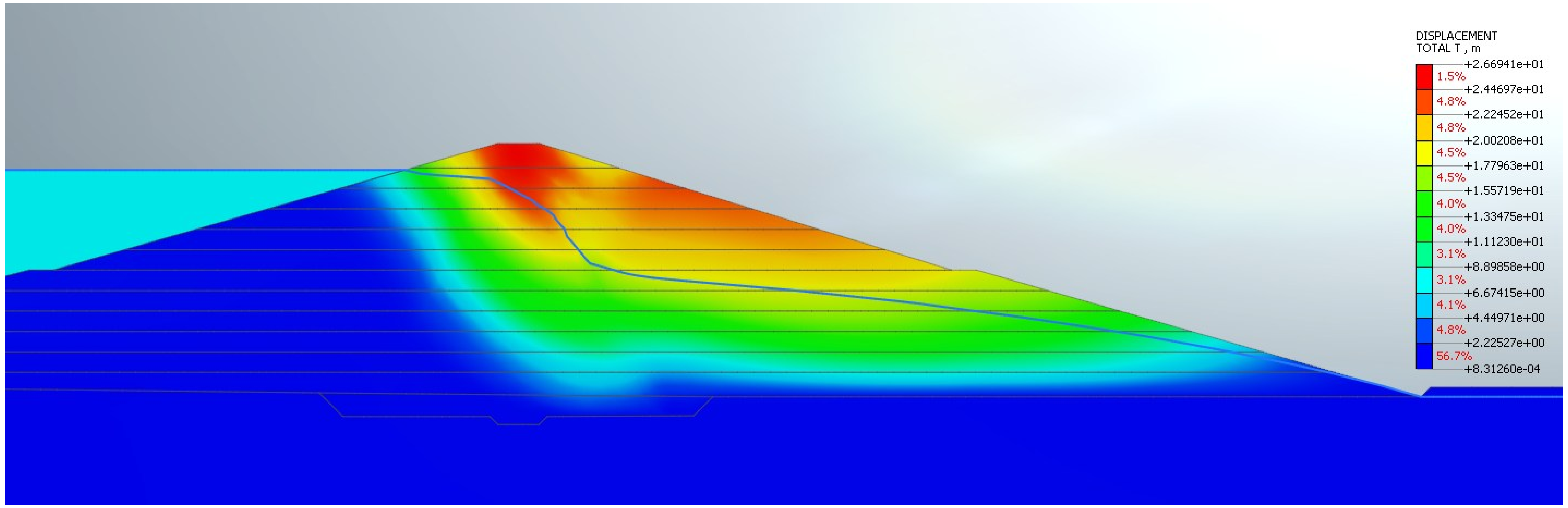
Results of SRM

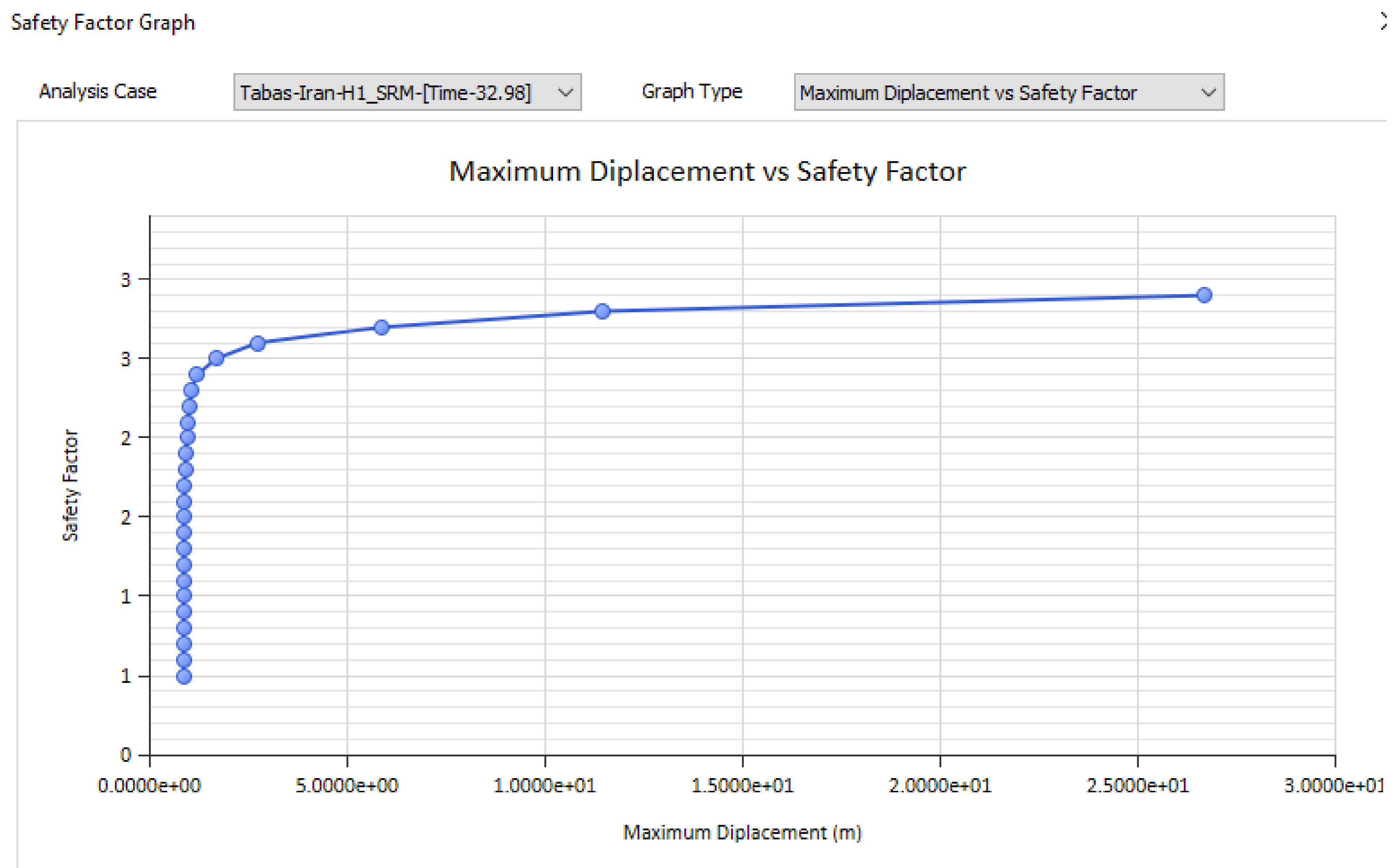
The SRM involves modelling subsurface materials as elastic-perfectly-plastic materials, while simultaneously reducing strengths by a strength reduction factor, R.

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

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

$$FOS = R_{max}$$





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

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