

# **Liquefaction Mechanisms of Upper and Lower San Fernando Dams in the 1971 Earthquake**

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11/10/2003

# Lower and Upper San Fernando Dams after 1971 Earthquake



Steinbrugge Collection, Earthquake Engineering Research Center  
University of California, Berkeley

Photo: Cluff, LLoyd

# Observations (Seed et al. 1973)

- Upper dam
  - Liquefied and weakened in certain zones;
  - A significant body of the hydraulic fill still retained considerable resistance;
  - Complete flow slide did not occur.
- Lower dam:
  - A large part of hydraulic fill liquefied;
  - The shear resistance of the soil could no longer withstand the initial driving forces;
  - Slide developed consequently.

# Question

- Why the two dams responded so differently to the same earthquake?

Given that they were

- founded on similar natural alluvium
- constructed using similar borrowing material and similar hydraulic filling method
- located only two miles away from each other

# Objective of the Numerical Analysis

- To investigate the failure and deformation mechanism of the San Fernando dams
  - Fully coupled finite element procedure (SUMDES2D, Li & Ming 2001)
  - Bounding surface critical state model (Li & Dafalias 2000, Li 2002)

# Fully-coupled Approach

- Physical Laws

- Balance of Linear Momentum

$$\sigma_{ij,j} - \rho b_i = -\rho \ddot{u}_i$$

- Conservation of Mass

$$q_{j,j} + n\dot{\epsilon}_{vwc} = \dot{\epsilon}_v$$

- Three Constitutive Relationships

- Soil skeleton

$$\Delta\sigma_{ij} = D_{ijkl}\Delta\varepsilon_{kl} + H_{ijkl}\Delta\dot{\varepsilon}_{kl}$$

- Pore fluid

$$\Delta u_w = \Gamma_w \Delta\varepsilon_{vwc}$$

- Interaction between solid and fluid phases

$$\Delta q_j = k_{ij}^* \left[ \rho_w (\Delta b_i - \Delta \ddot{u}_i) - \Delta u_{w,i} \right]$$

# State-Dependent Dilatancy Model

- **Stress Dilatancy Theory** (Rowe 1962)

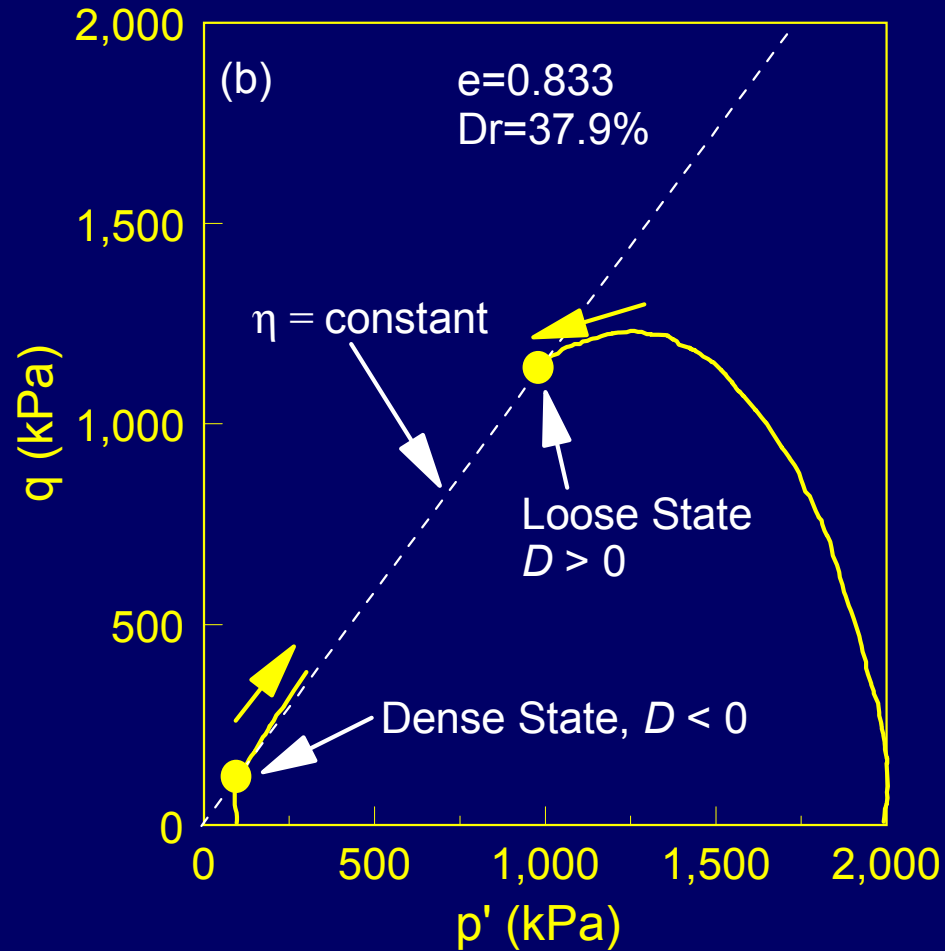
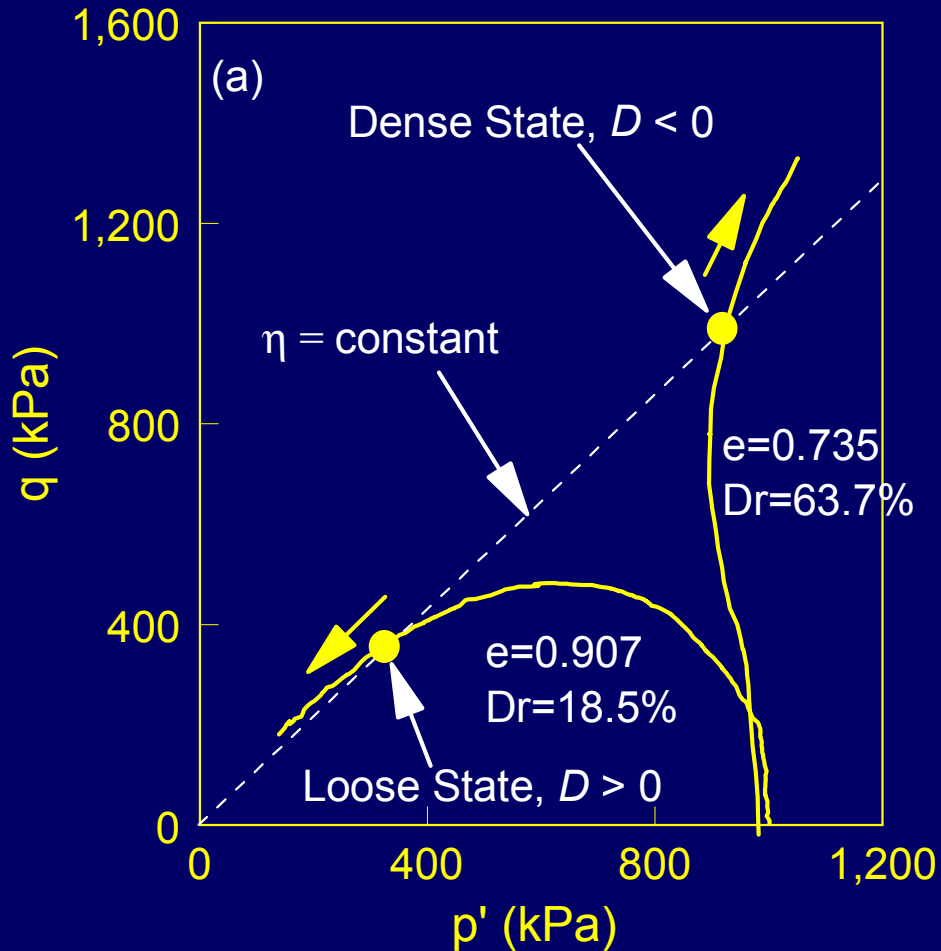
$$D = D(\eta, C)$$

- **State-Dependent Dilatancy** (Li and Dafalias 2000)

$$D = D(\eta, \psi, Q, C)$$

# Variation of Dilatancy

Test of Toyoura Sand (Verdugo and Ishihara 1996)

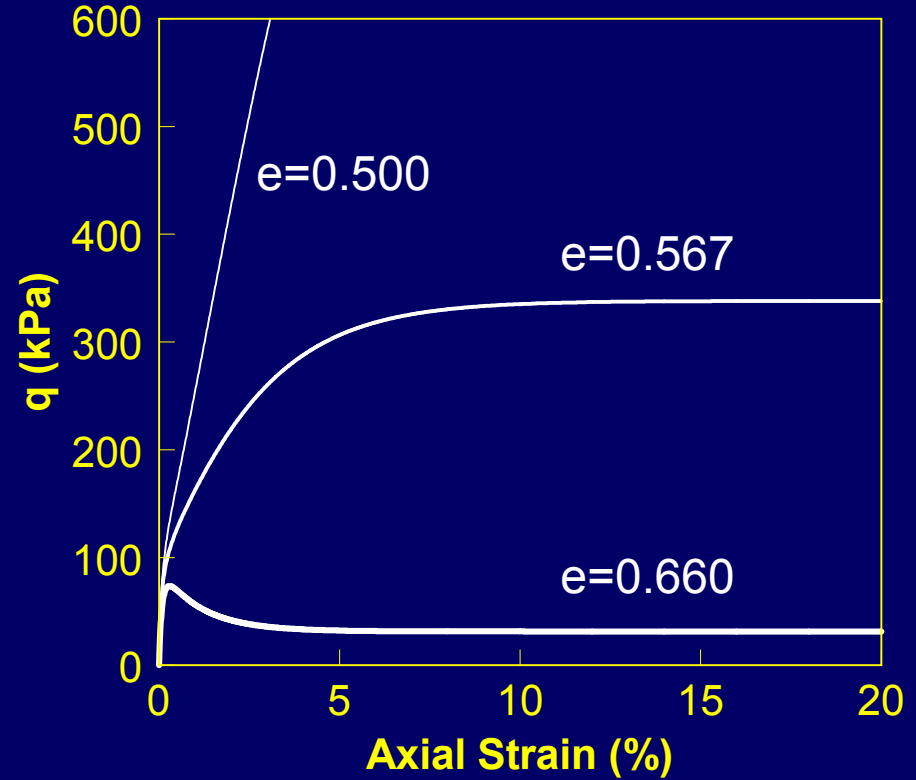
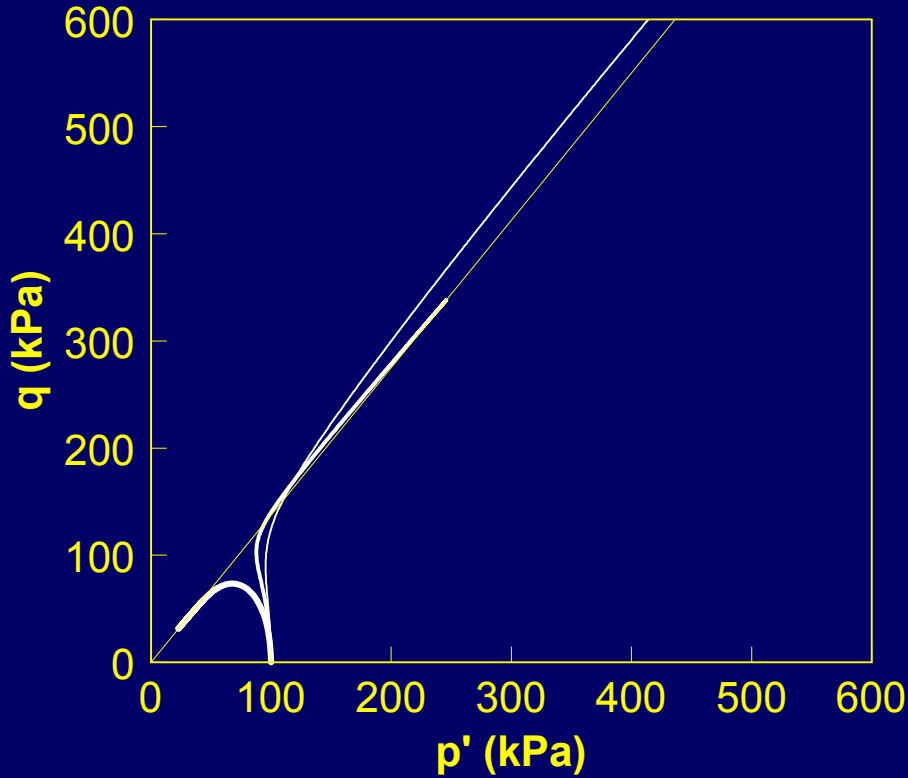


# Model Parameters based on SF7

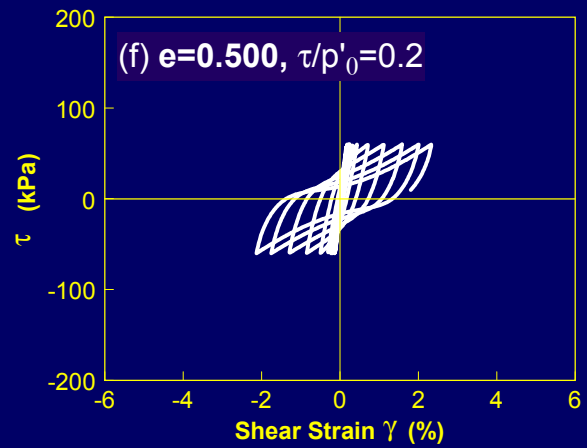
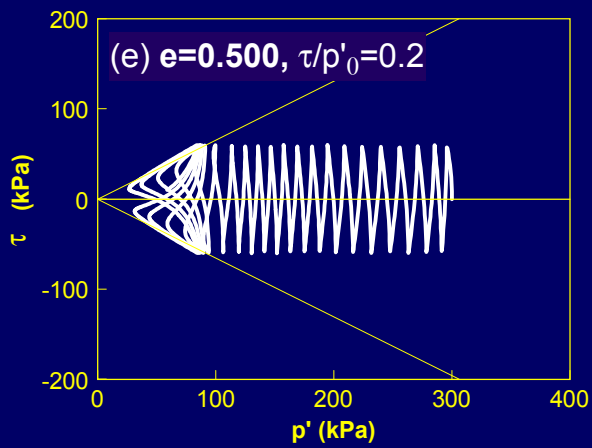
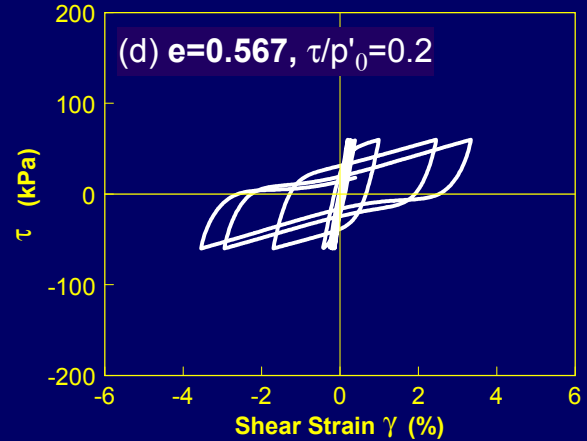
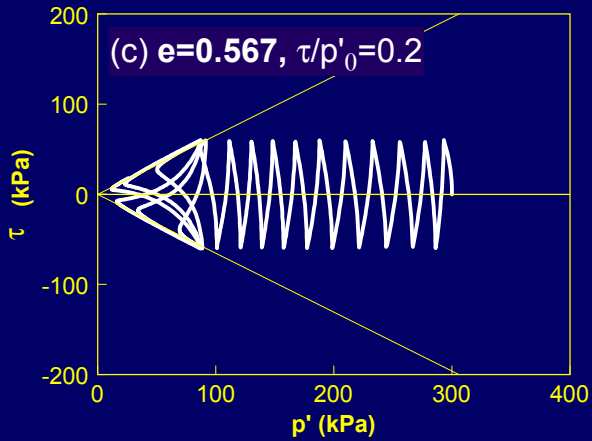
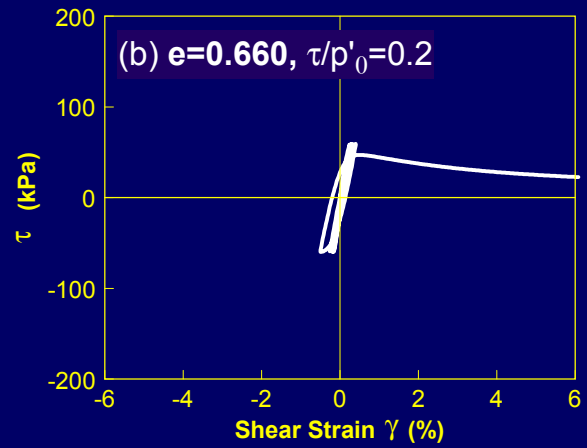
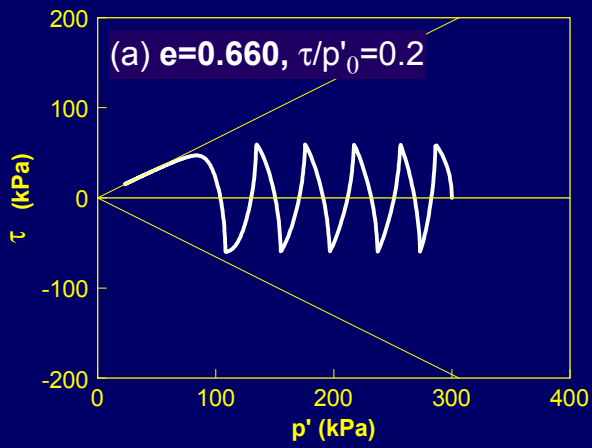
| Elastic parameters          | Critical State parameters   | Parameters associated with <i>dr</i> -mechanism                                       | Parameters associated with <i>dp</i> -mechanism | Default parameters                                    |
|-----------------------------|---|---|---|---|
| $G_0 = 125$<br>$\nu = 0.25$ | $M = 1.375$<br>$c = 0.7$<br>$e_T = 0.813$<br>$\lambda_c = 0.206$<br>$\xi = 0.2$ | $d_1 = 0.41$<br>$m = 3.5$<br>$h_1 = 3.15$<br>$h_2 = 3.05$<br>$h_3 = 2.2$<br>$n = 1.1$ | $d_2 = 1$<br>$h_4 = 3.5$                        | $a = 1$<br>$b_1 = 0.005$<br>$b_2 = 2$<br>$b_3 = 0.01$ |

(Based on data from Castro et al. 1989)

# Model Response

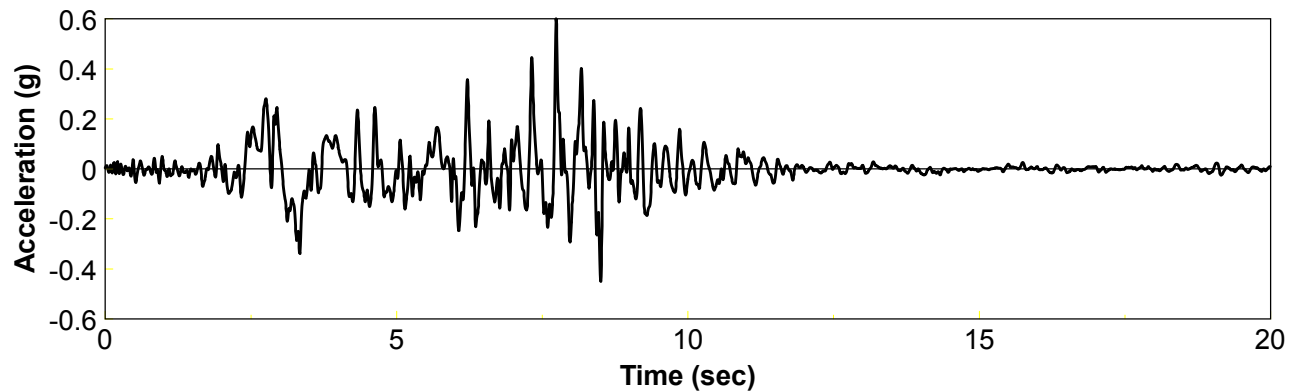
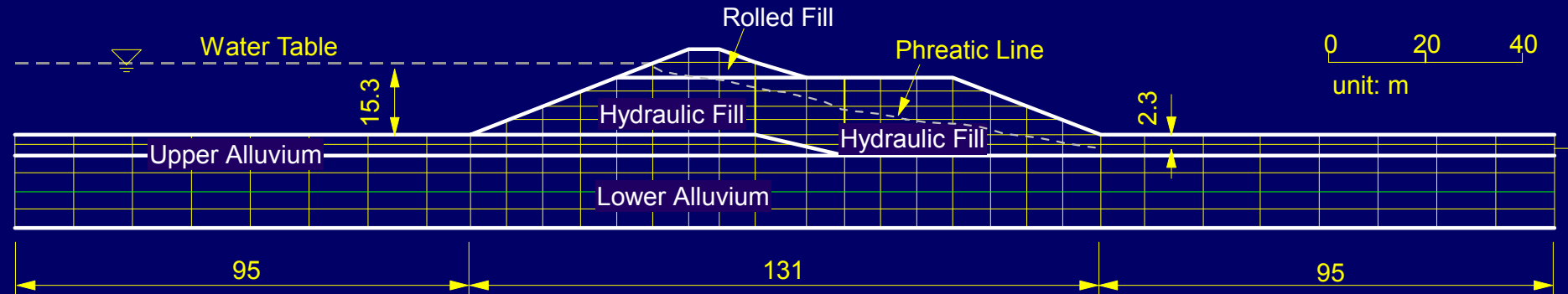


Undrained  
Triaxial  
Compression



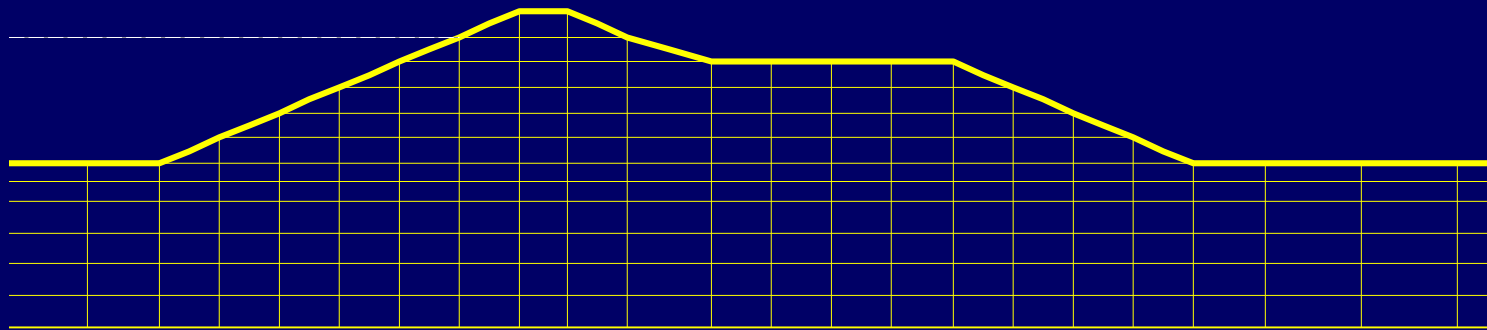
Undrained  
Cyclic  
Simple  
Shear

# Upper San Fernando Dam

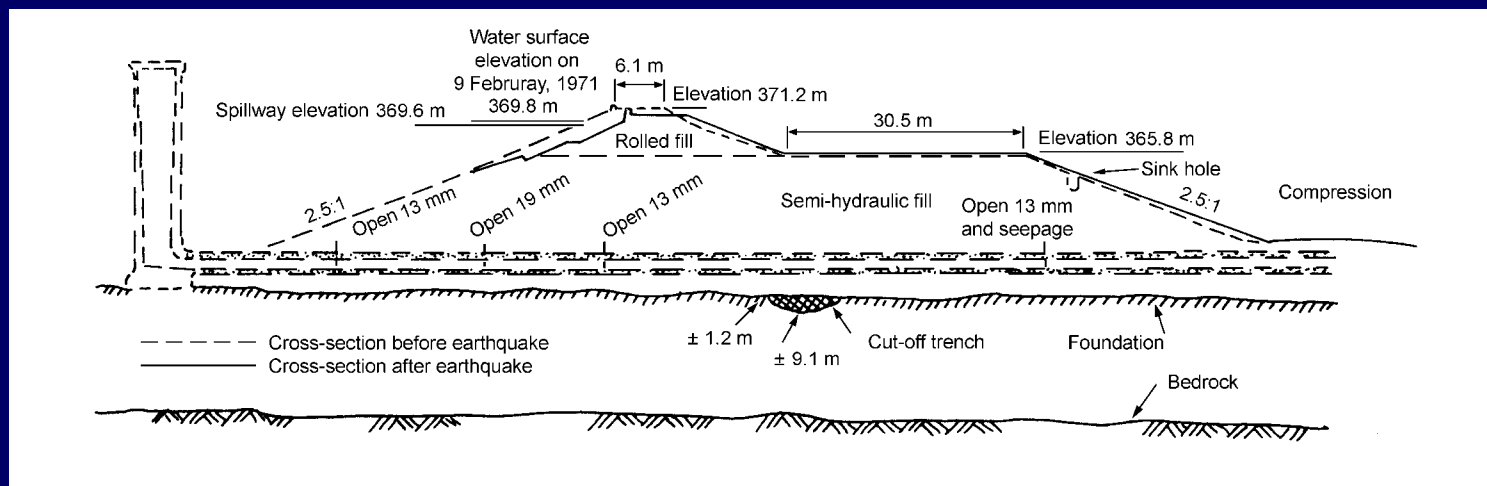
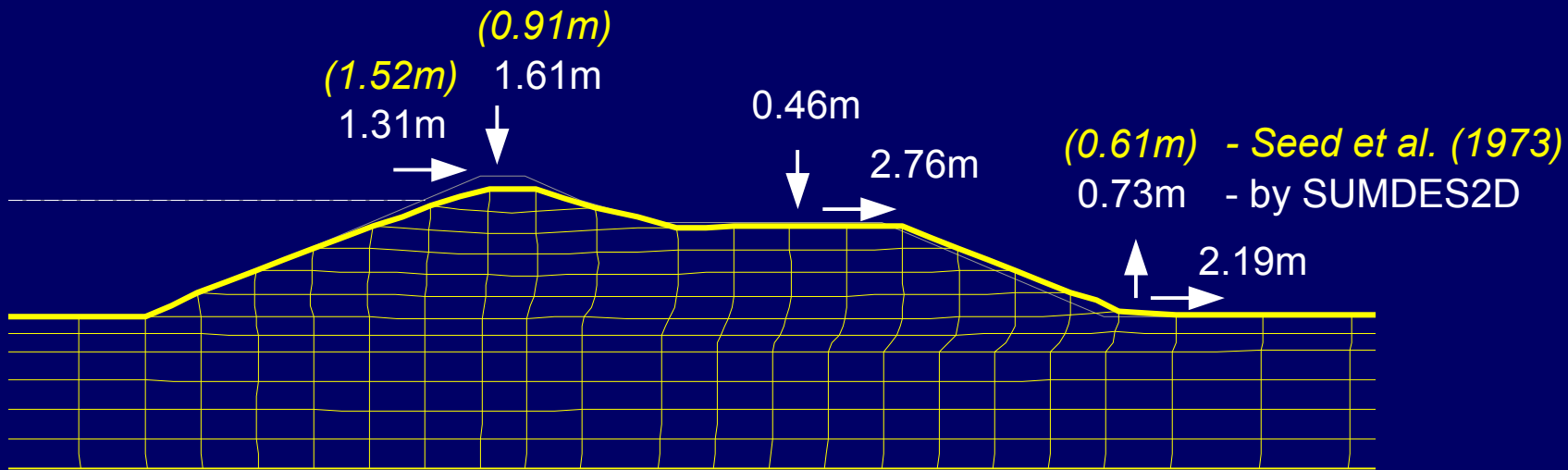


# Flow Deformation of the Upper dam $t = 00$ sec

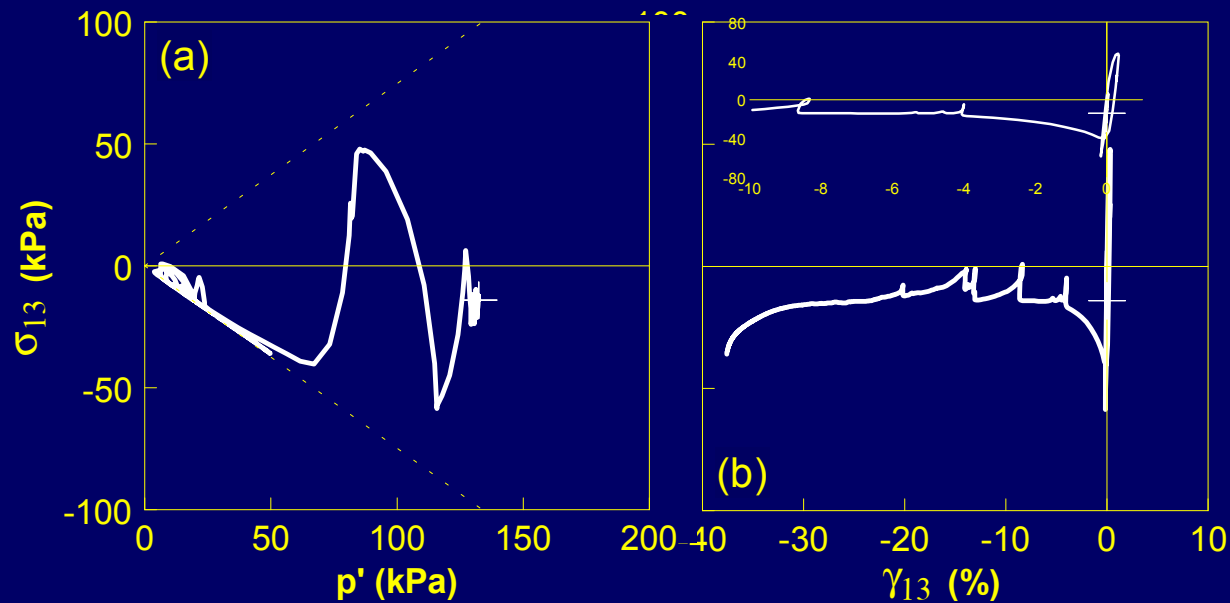
Click on the mesh to start the animation



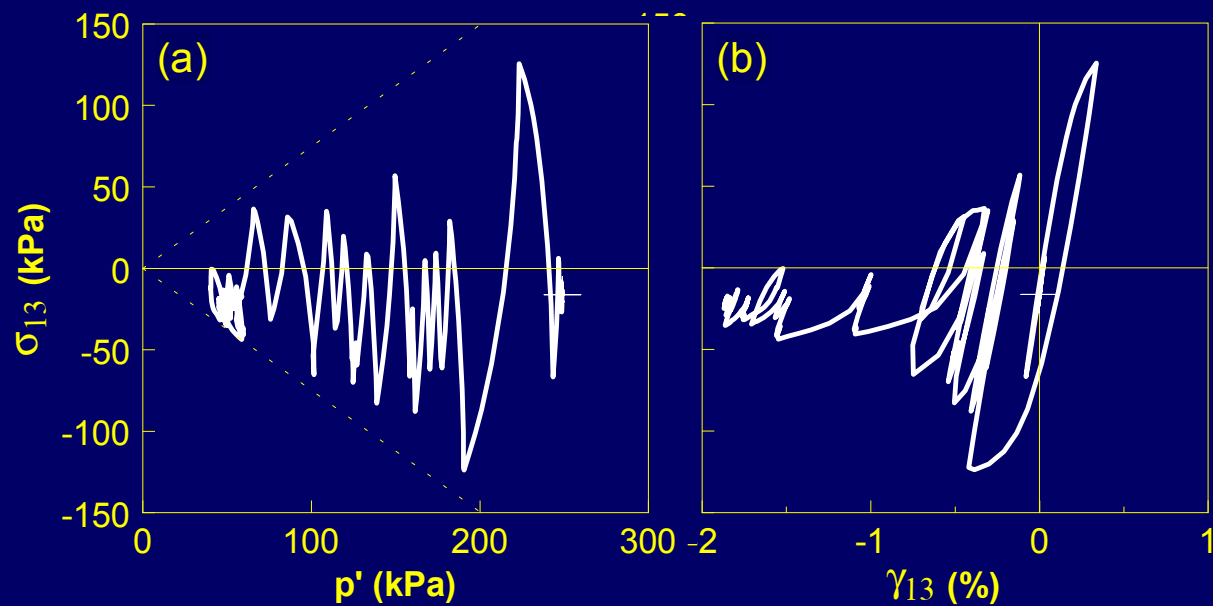
# Flow Deformation of the Upper dam $t = 40$ sec



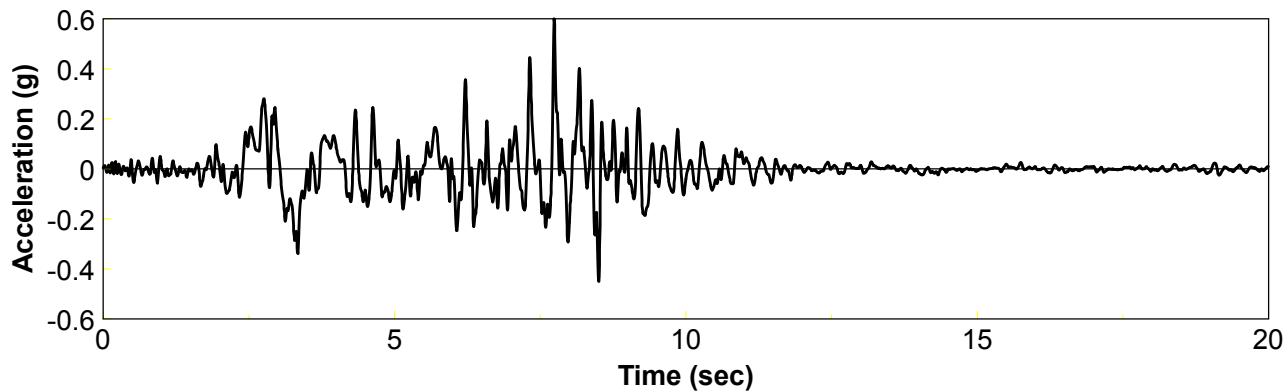
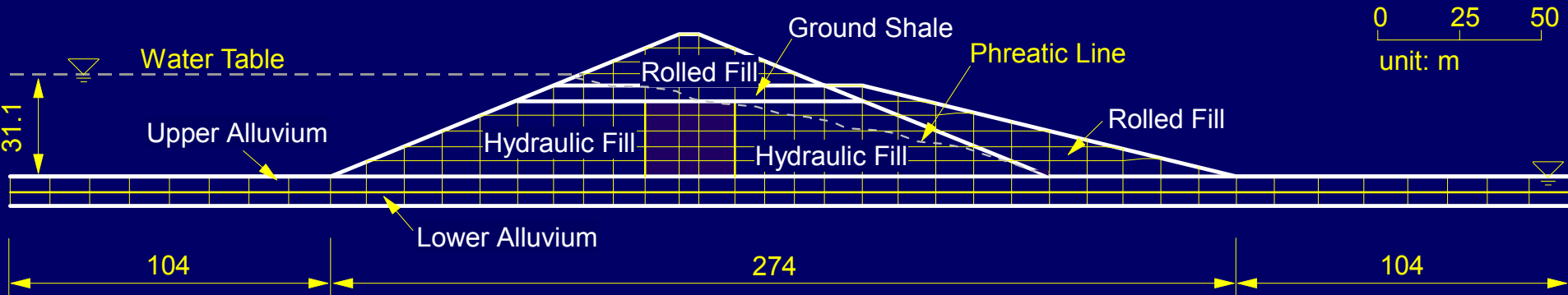
# Typical response of hydraulic fill material



# Typical response of alluvium in foundation

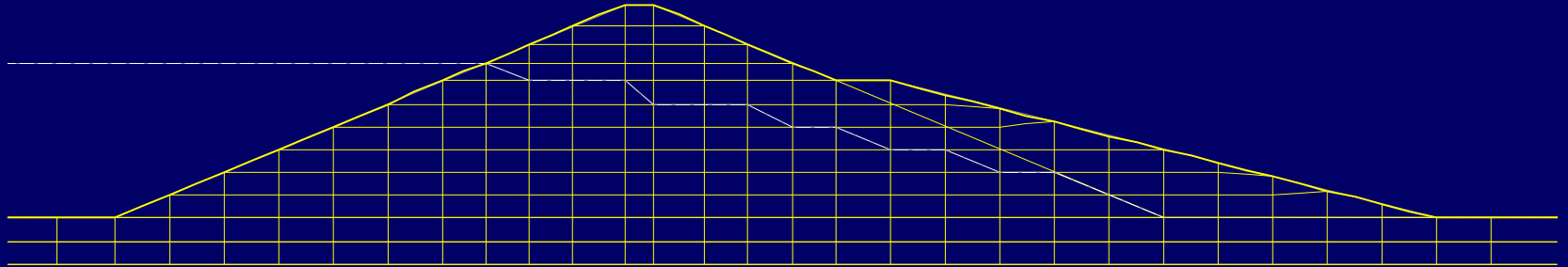


# Lower San Fernando Dam

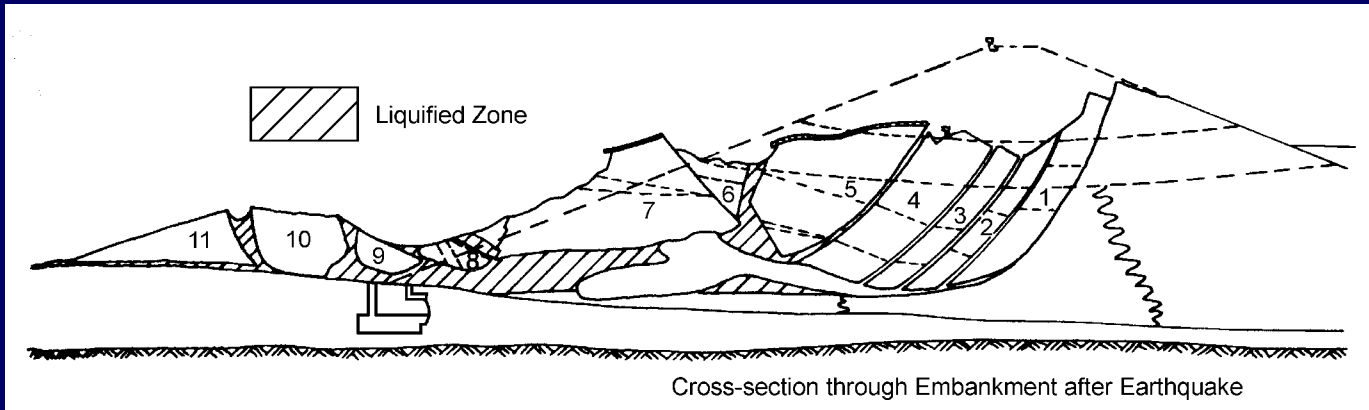
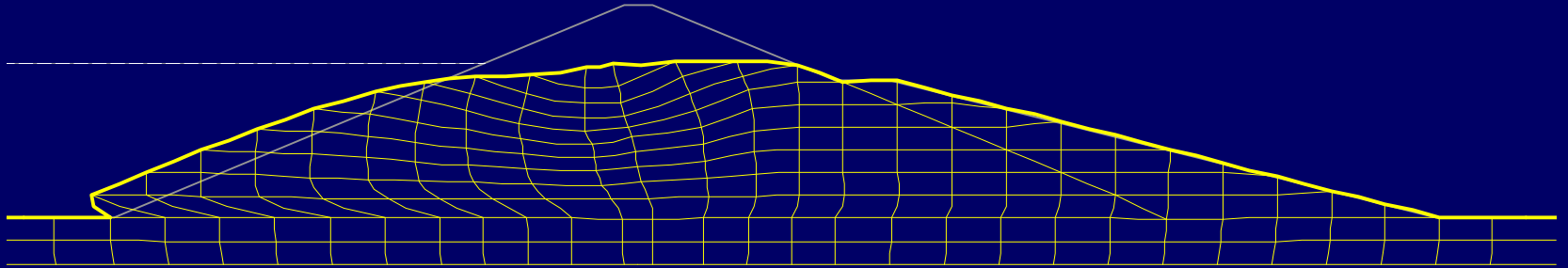


# Flow Failure of the Lower Dam $t = 00$ sec

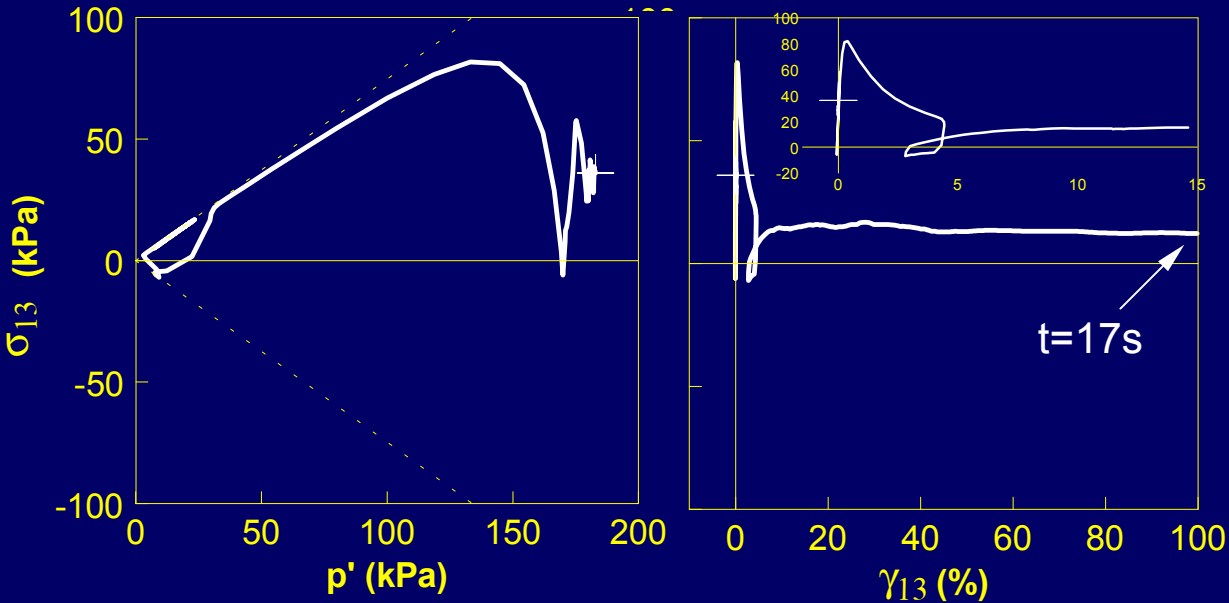
Click on the mesh to start the animation



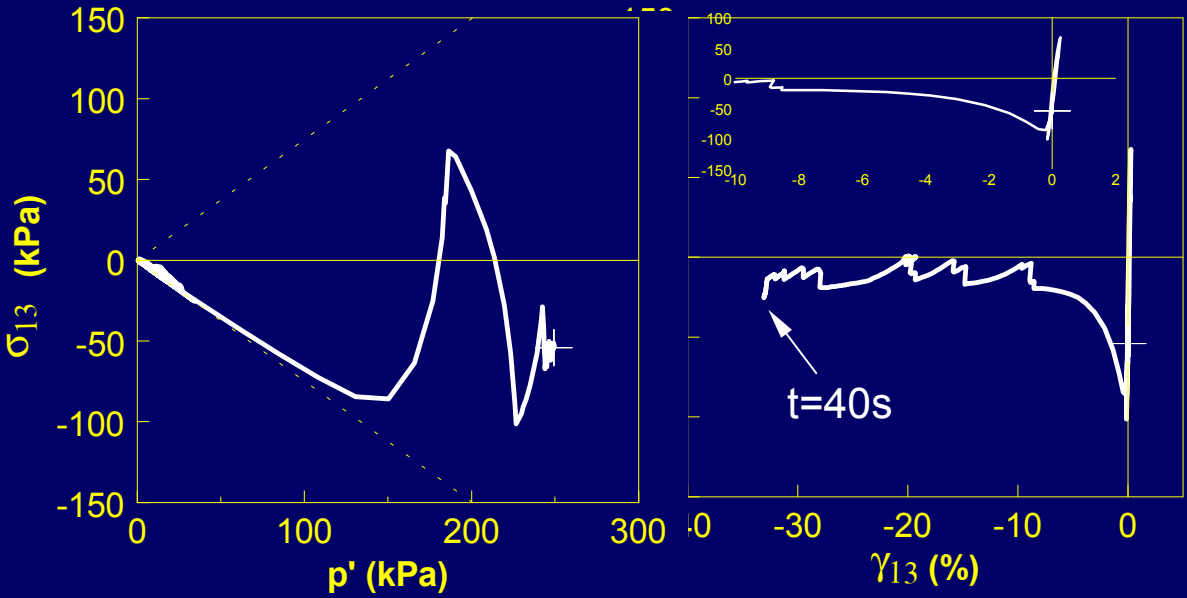
# Flow Failure of the Lower Dam $t = 40$ sec



# Response of soil in lower part of hydraulic fill (upstream side)

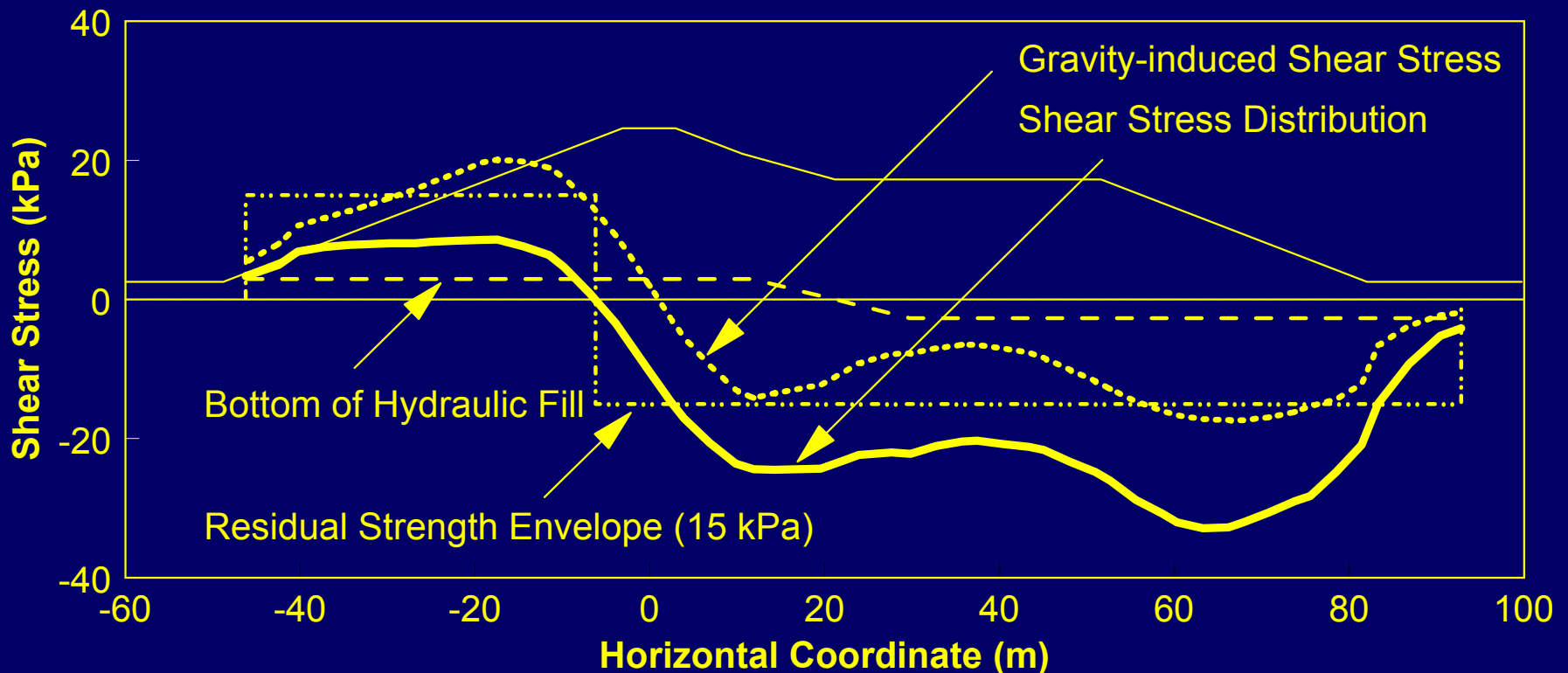


# Response of soil in lower part of hydraulic fill (downstream side)



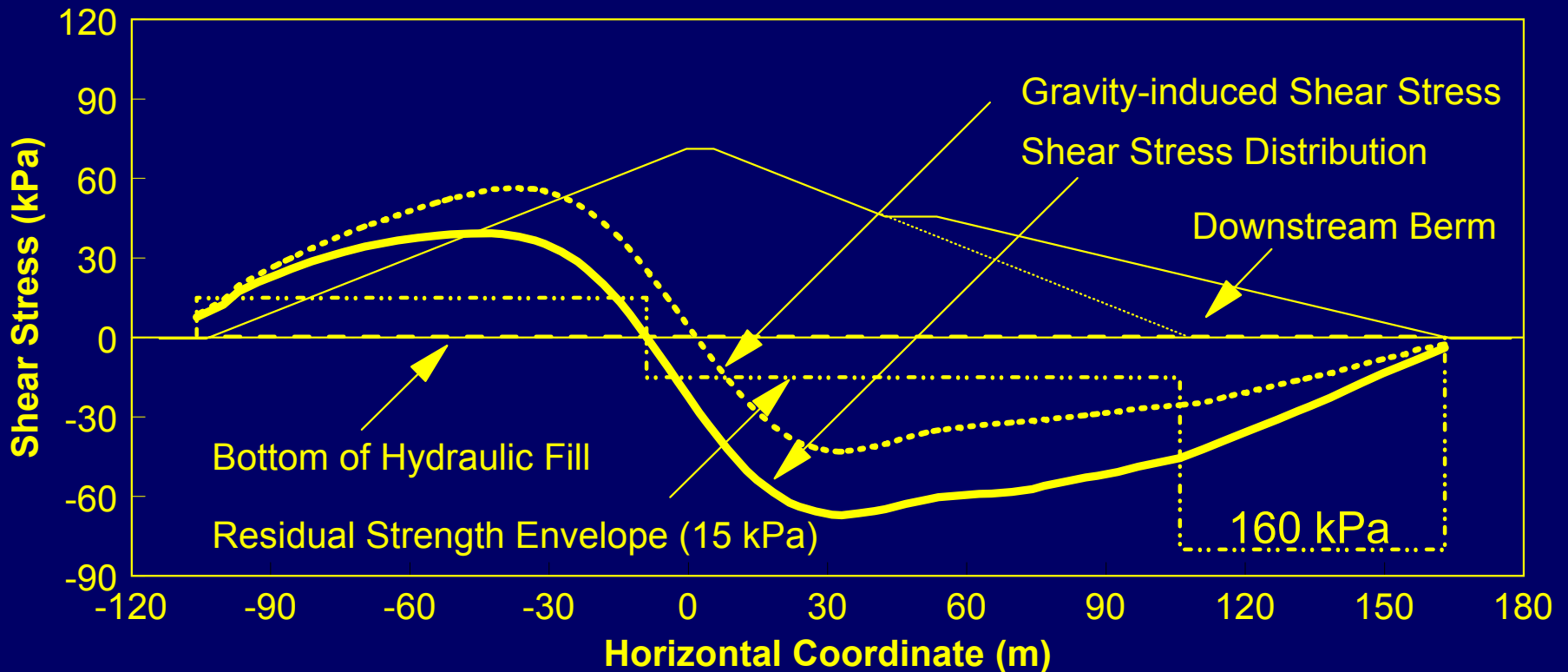
# Shear Stress Distribution along the Bottom of the Hydraulic fill in Embankment

(a) Upper San Fernando Dam



# Shear Stress Distribution along the Bottom of the Hydraulic fill in Embankment

(b) Lower San Fernando Dam



# Conclusions

1. Upper Dam: The static driving forces were marginally higher than the steady state strength of the hydraulic fill only on the downstream side. As a result, the dam moved downstream restrictively upon liquefaction.
2. Lower Dam: The static driving forces were significantly higher than the steady state strength of the hydraulic fill on both sides of the embankment. However, as the downstream hydraulic fill was supported by the well constructed downstream berm, the liquefied soil moved towards the reservoir.

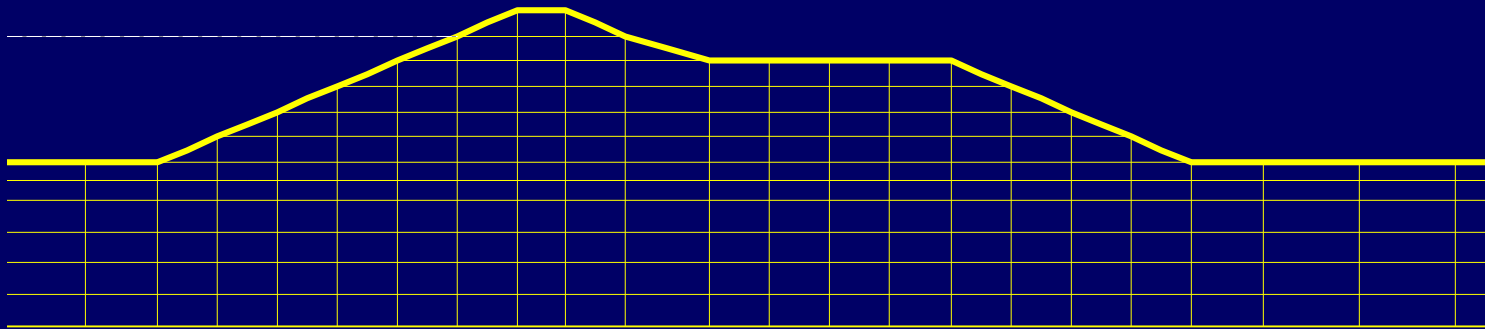
3. Fully coupled procedure that incorporates an appropriate soil model can be used as an effective tool to study the failure and deformation mechanisms of earth dams.

**Thank you**

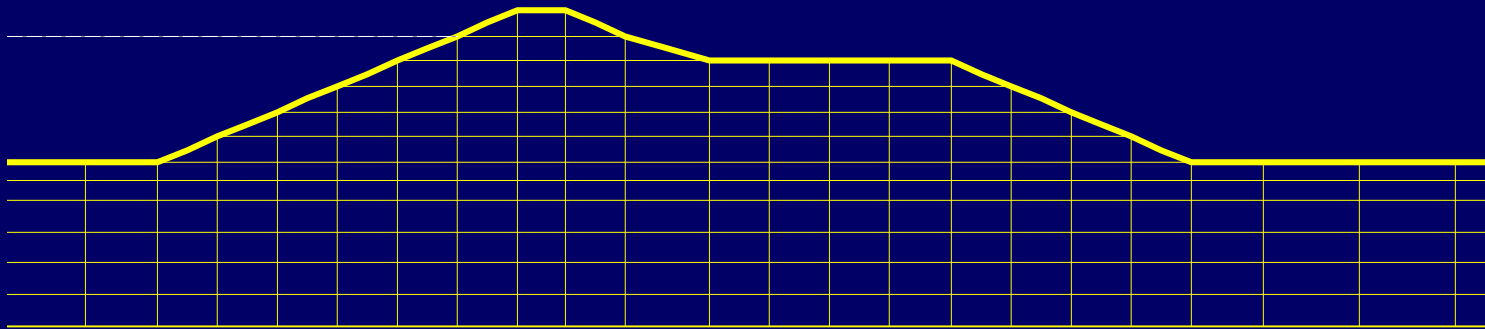
# Animation USF

- flow failure

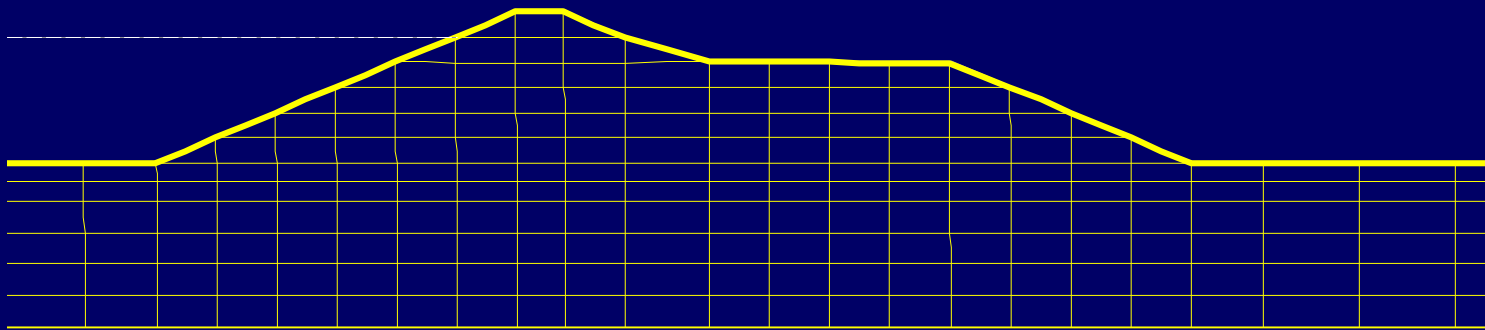
Flow Deformation of the Upper dam  $t = 01$ sec



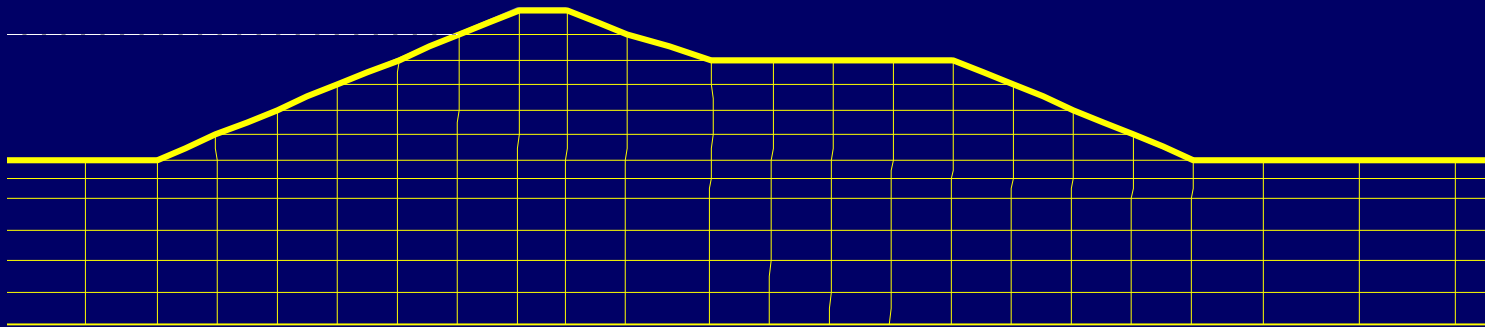
Flow Deformation of the Upper dam  $t = 02$ sec



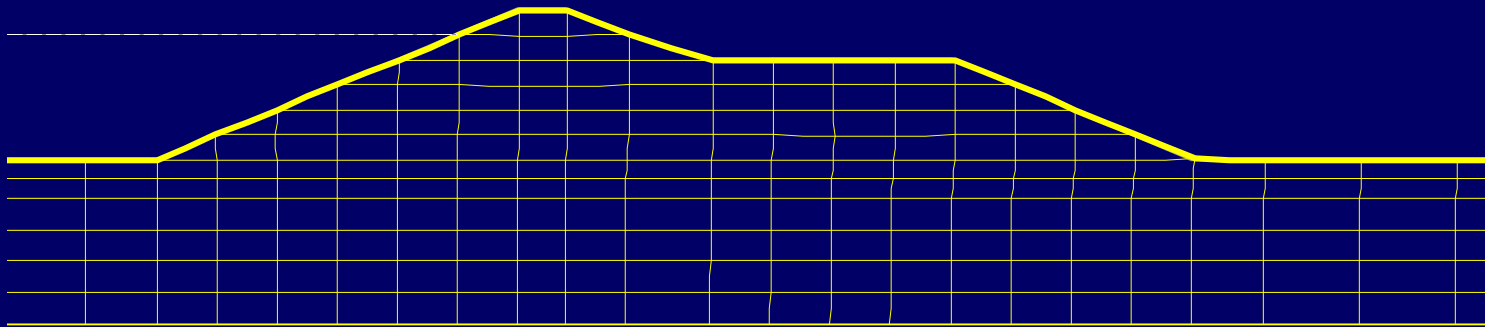
Flow Deformation of the Upper dam  $t = 03$ sec



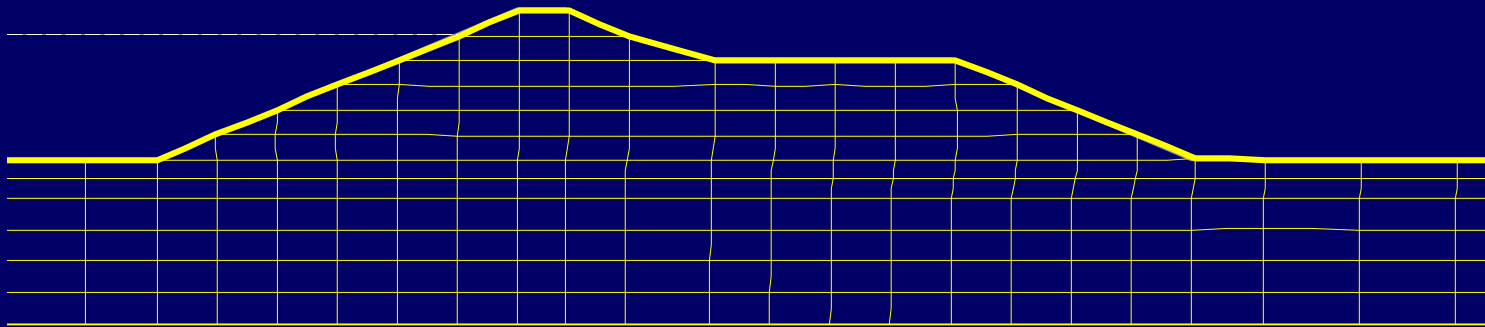
Flow Deformation of the Upper dam  $t = 04$ sec



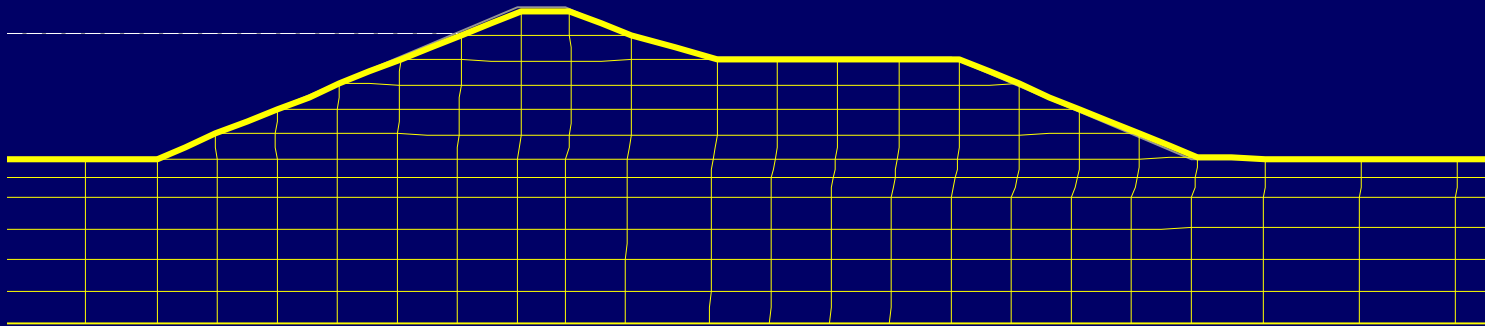
Flow Deformation of the Upper dam  $t = 05$ sec



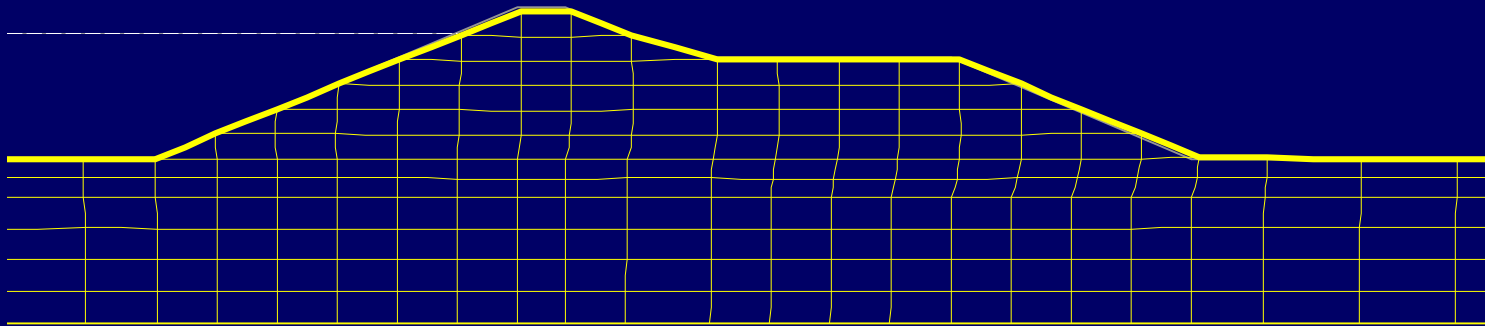
Flow Deformation of the Upper dam t = 06sec



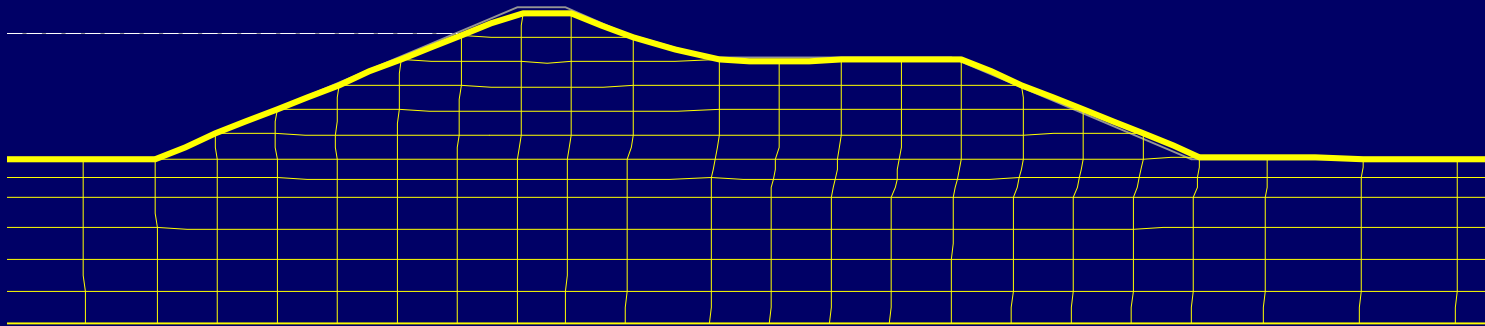
Flow Deformation of the Upper dam  $t = 07$  sec



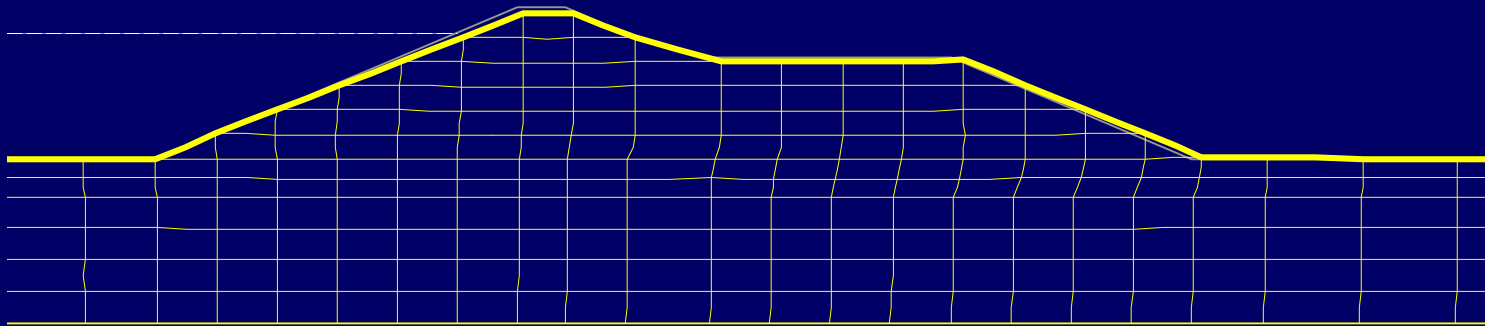
Flow Deformation of the Upper dam t = 08sec



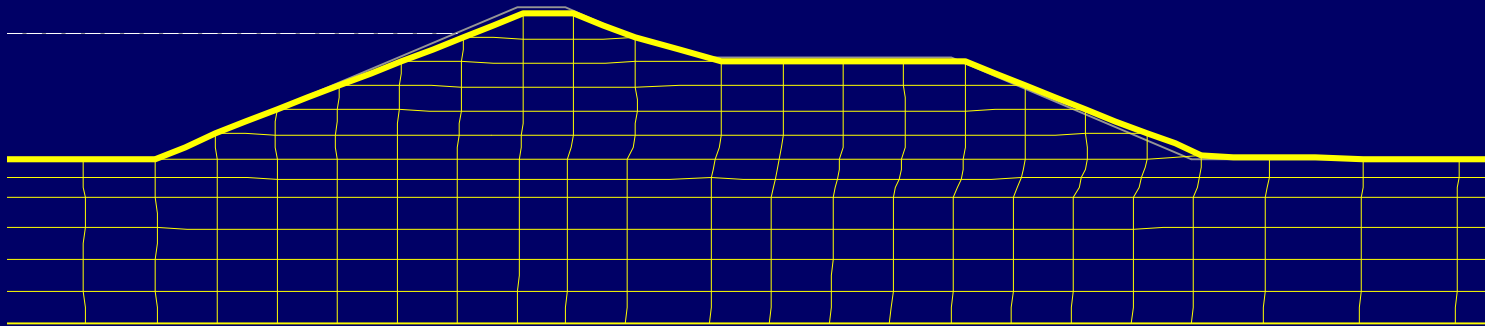
Flow Deformation of the Upper dam  $t = 09$ sec



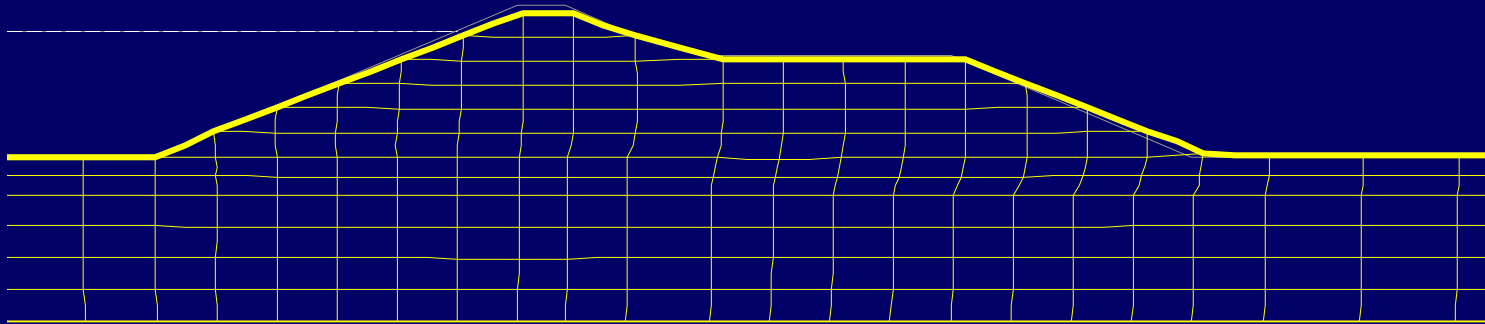
Flow Deformation of the Upper dam  $t = 10$ sec



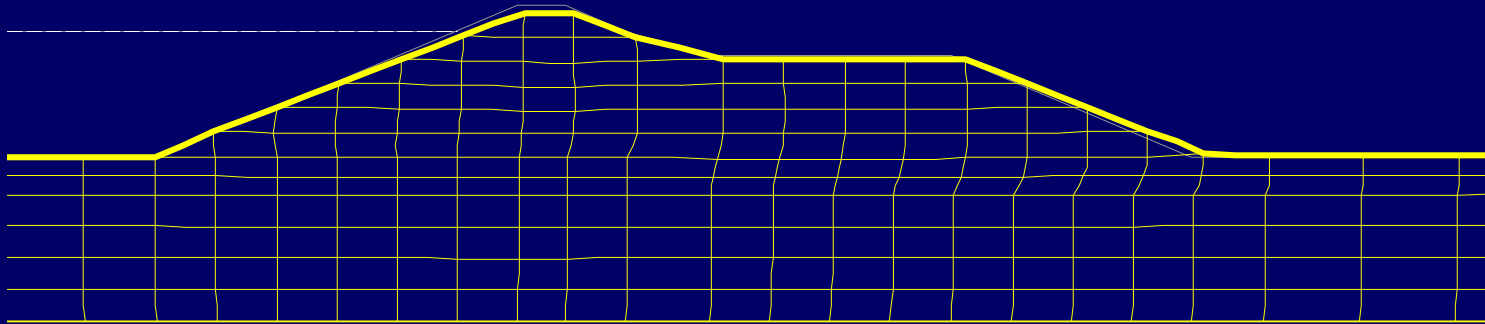
Flow Deformation of the Upper dam  $t = 11$ sec



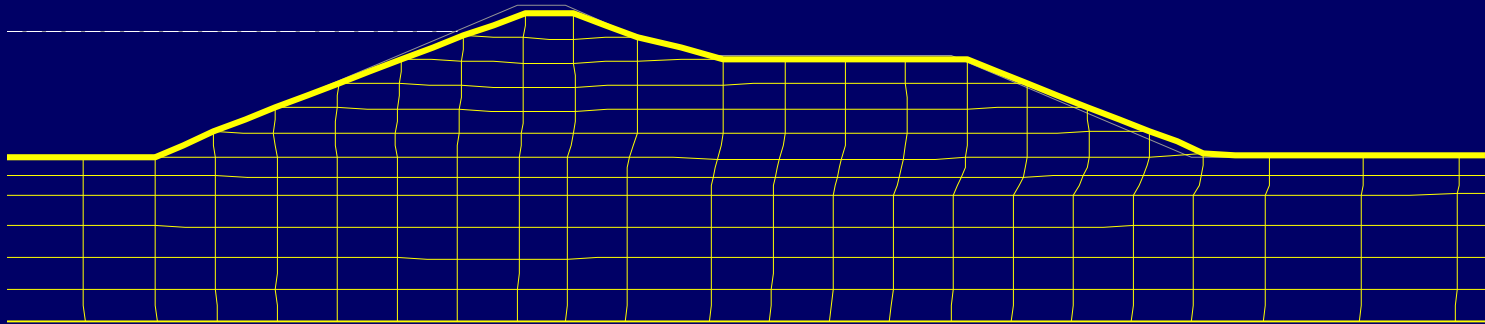
# Flow Deformation of the Upper dam $t = 12$ sec



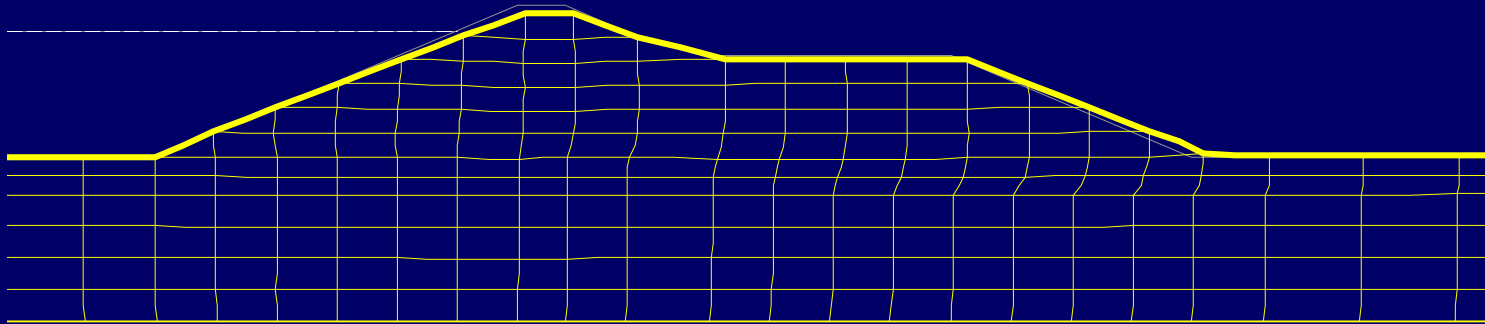
Flow Deformation of the Upper dam  $t = 13$ sec



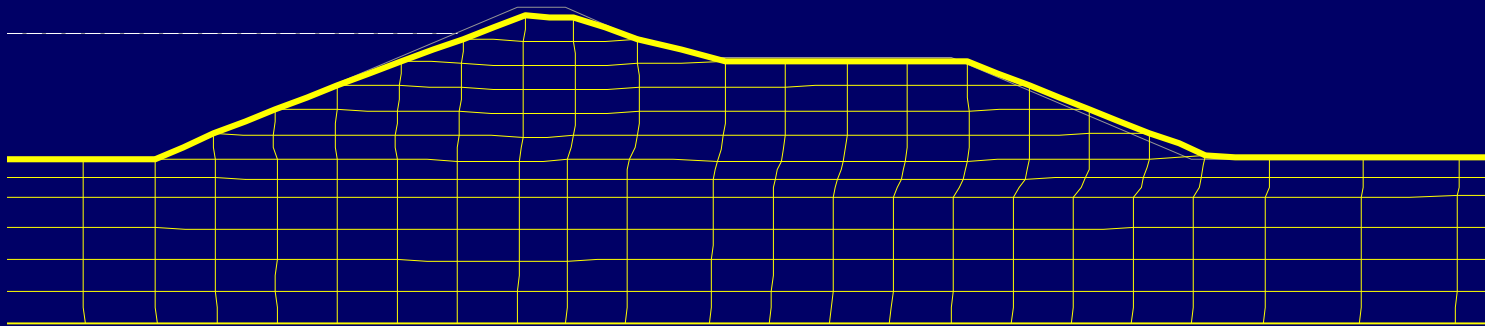
Flow Deformation of the Upper dam  $t = 14$ sec



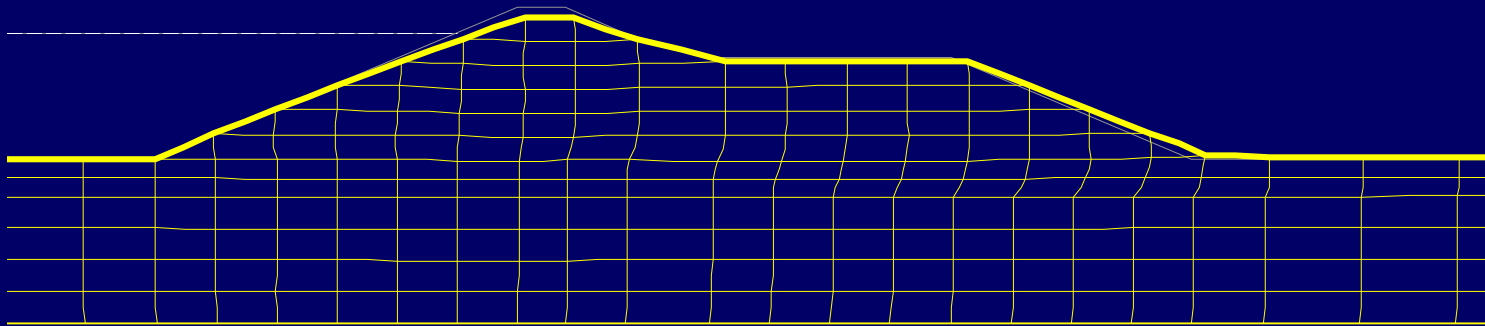
Flow Deformation of the Upper dam  $t = 15$ sec



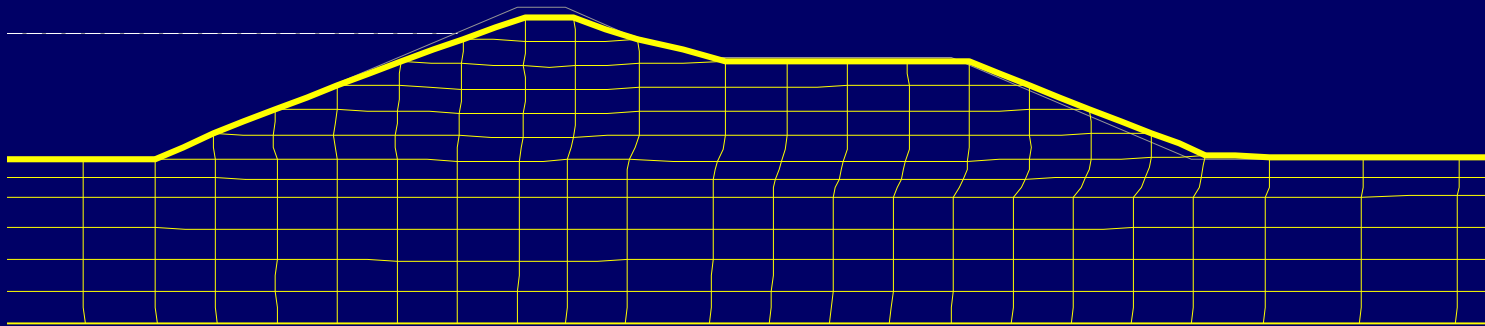
Flow Deformation of the Upper dam  $t = 16$ sec



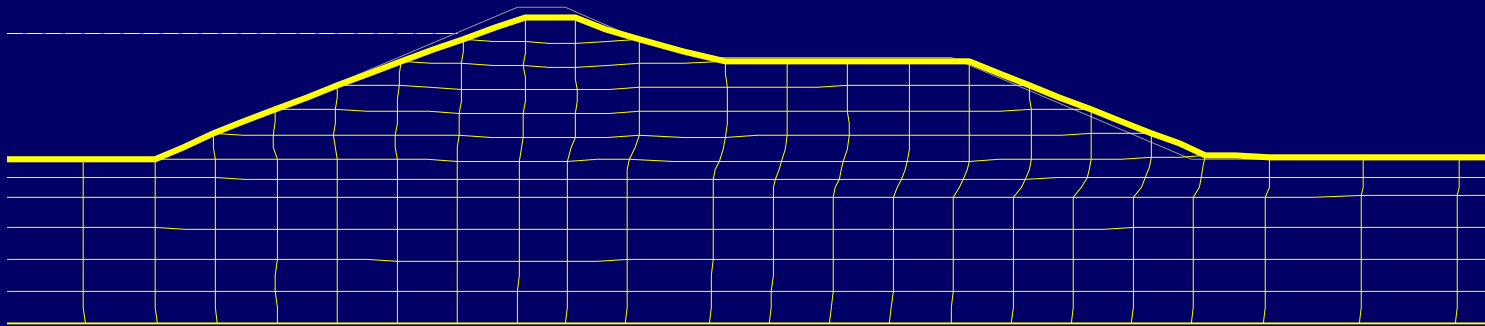
Flow Deformation of the Upper dam  $t = 17$  sec



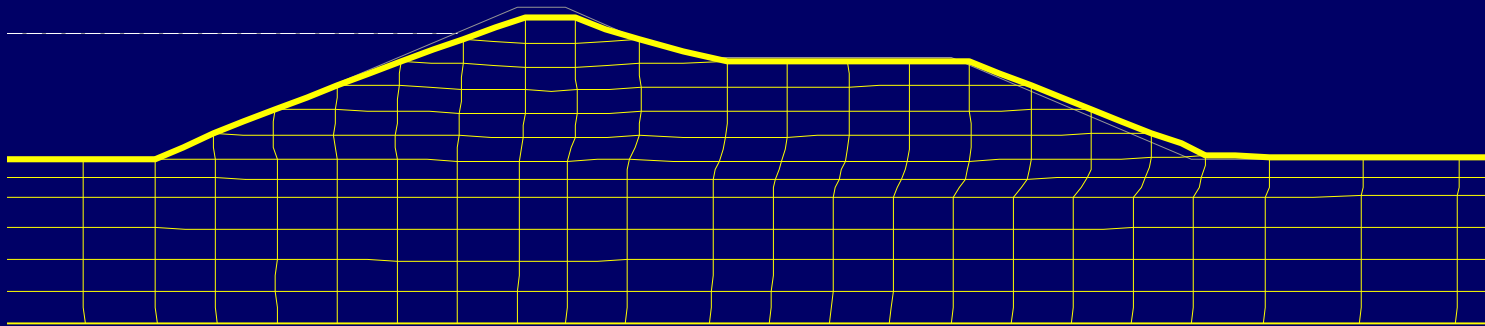
# Flow Deformation of the Upper dam $t = 18$ sec



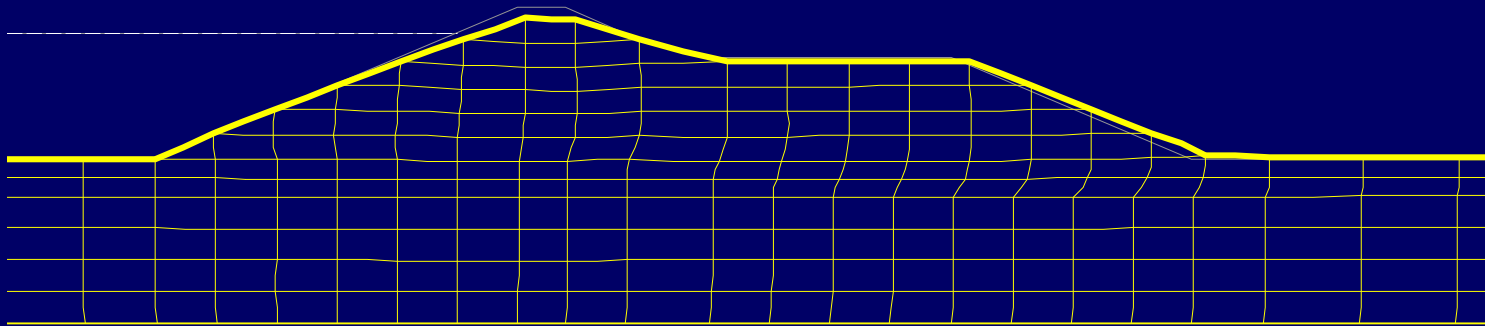
Flow Deformation of the Upper dam  $t = 19$ sec



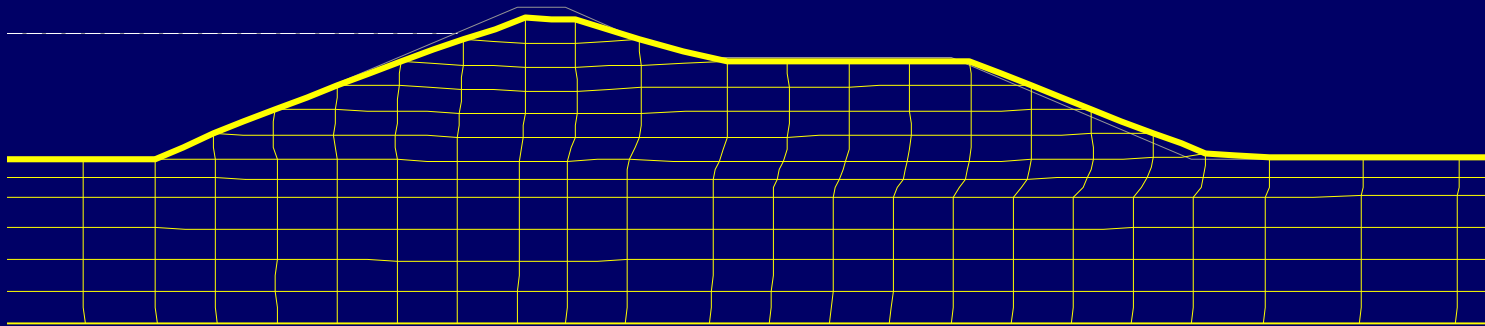
Flow Deformation of the Upper dam  $t = 20$ sec



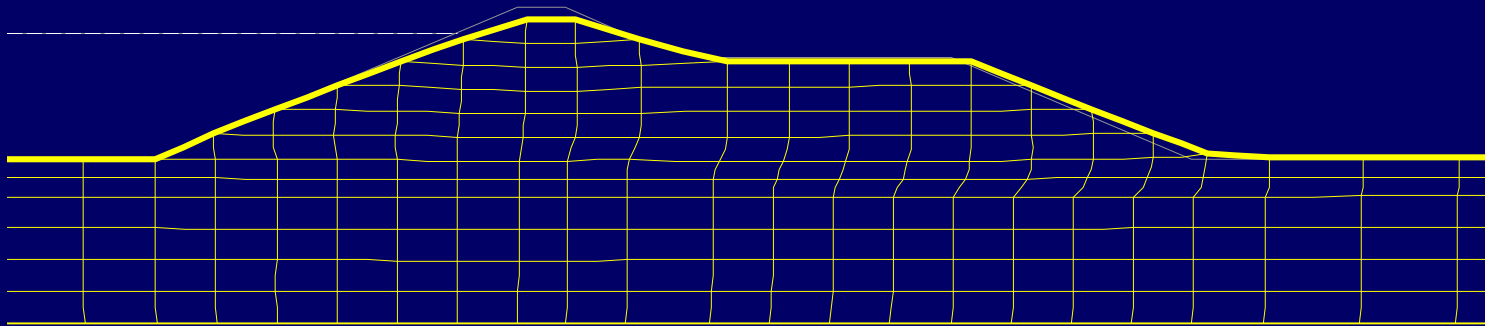
Flow Deformation of the Upper dam  $t = 21$ sec



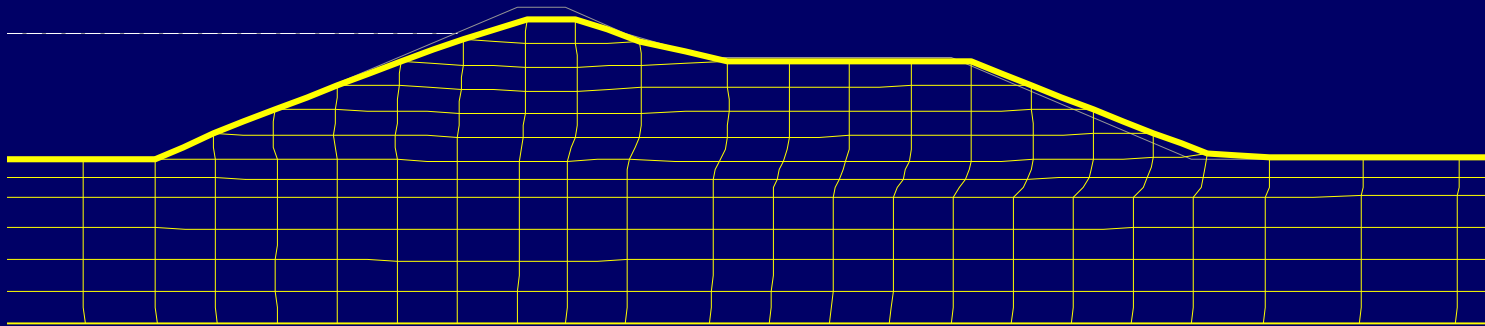
Flow Deformation of the Upper dam  $t = 22$ sec



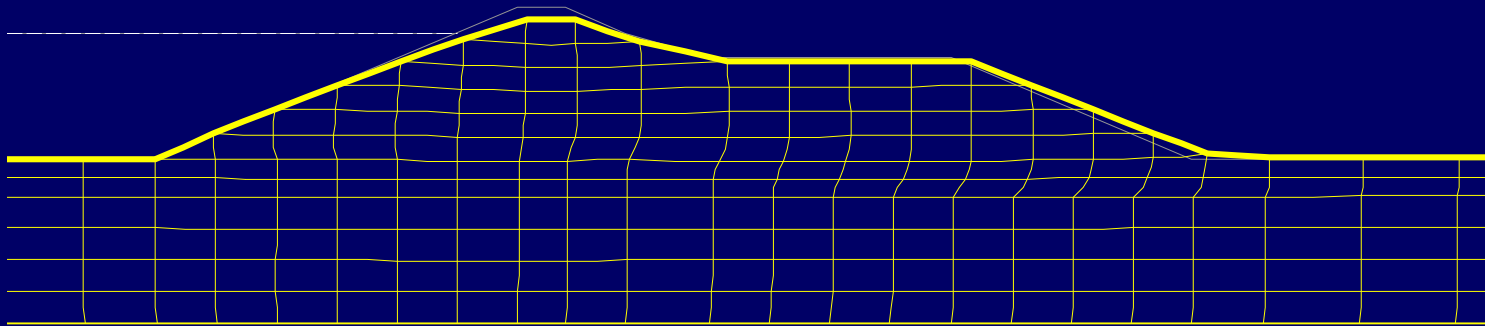
Flow Deformation of the Upper dam  $t = 23$ sec



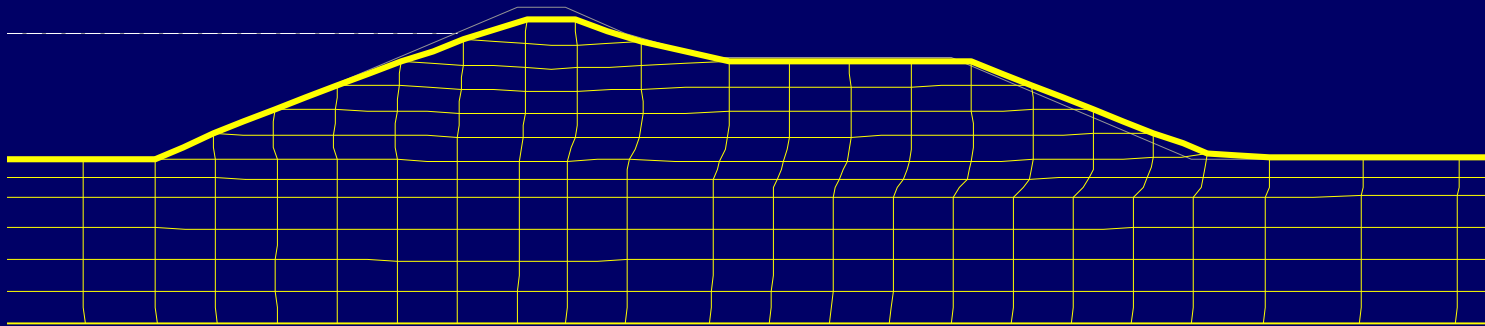
Flow Deformation of the Upper dam  $t = 24$ sec



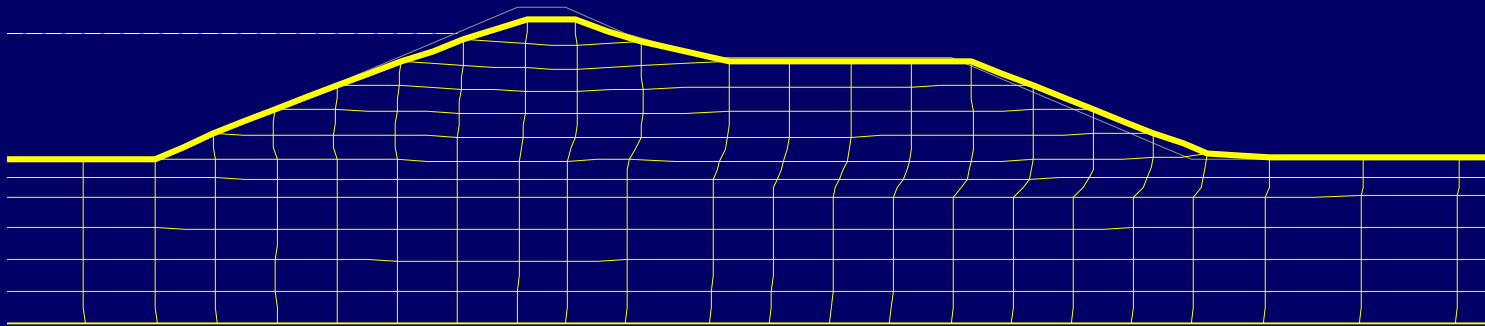
Flow Deformation of the Upper dam  $t = 25$ sec



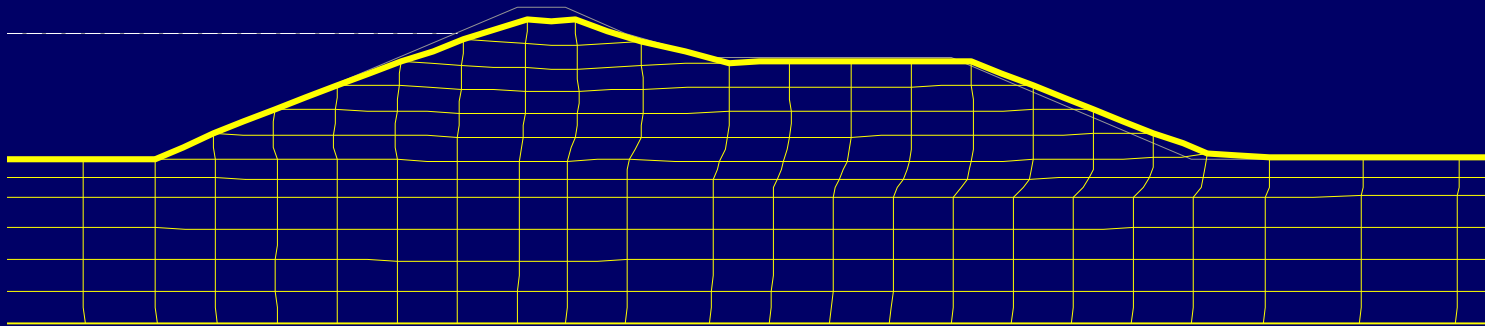
Flow Deformation of the Upper dam  $t = 26$ sec



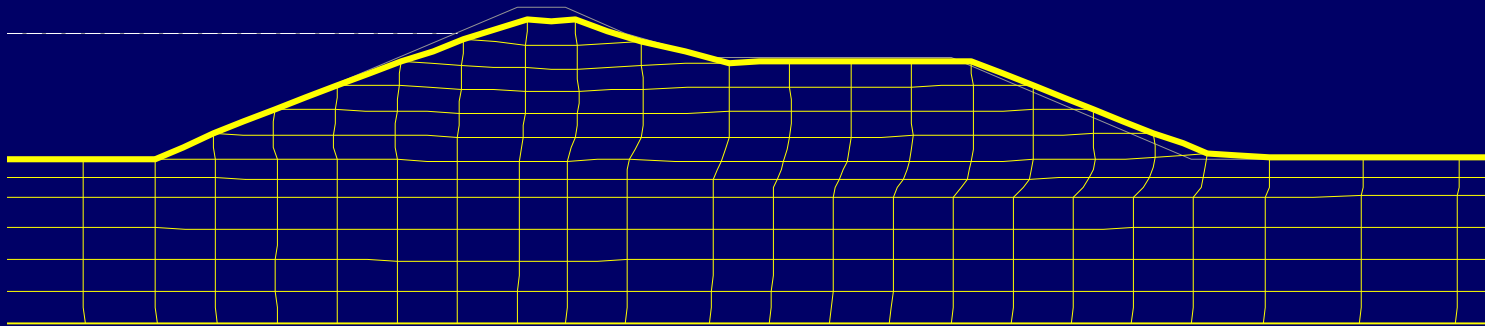
Flow Deformation of the Upper dam  $t = 27$  sec



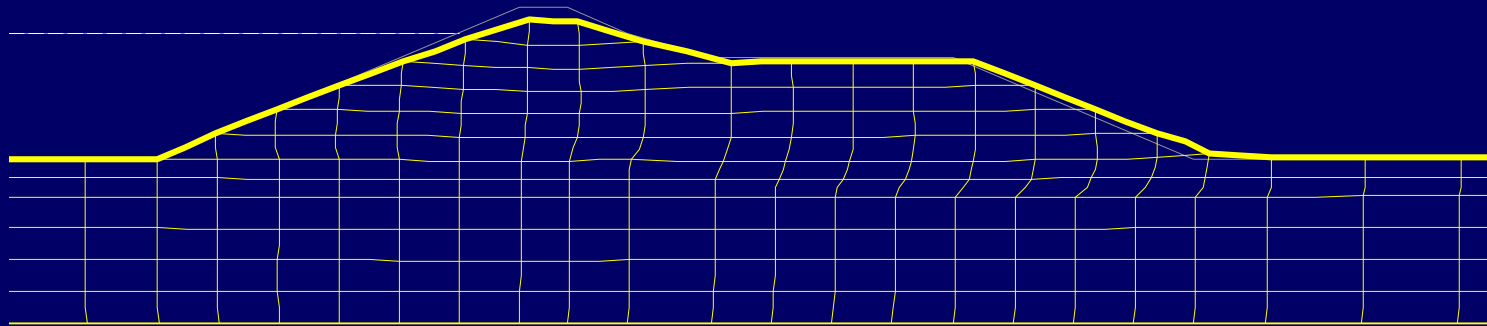
Flow Deformation of the Upper dam  $t = 28$ sec



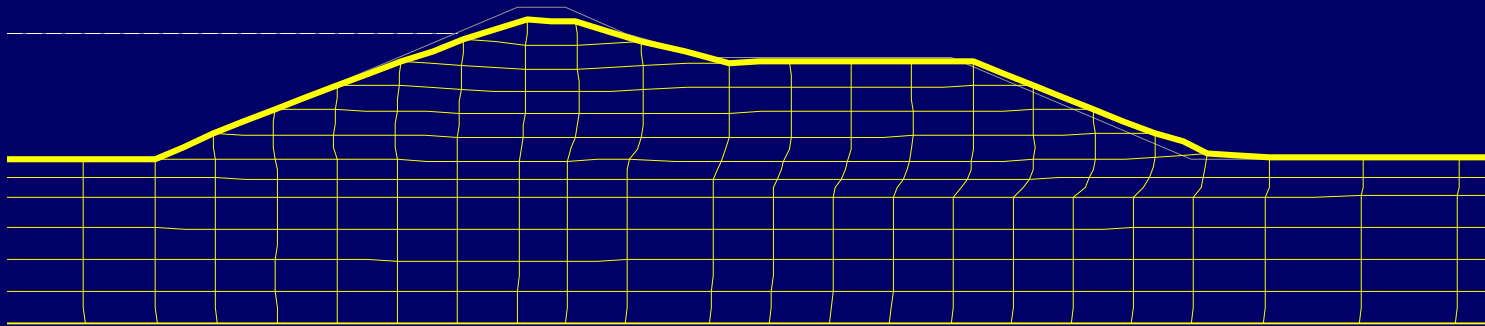
Flow Deformation of the Upper dam  $t = 29$ sec



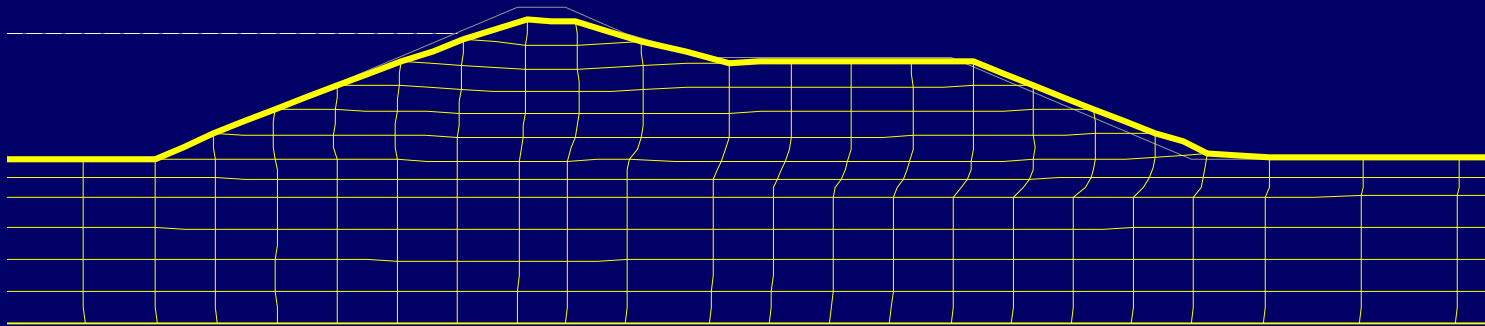
Flow Deformation of the Upper dam  $t = 30$ sec



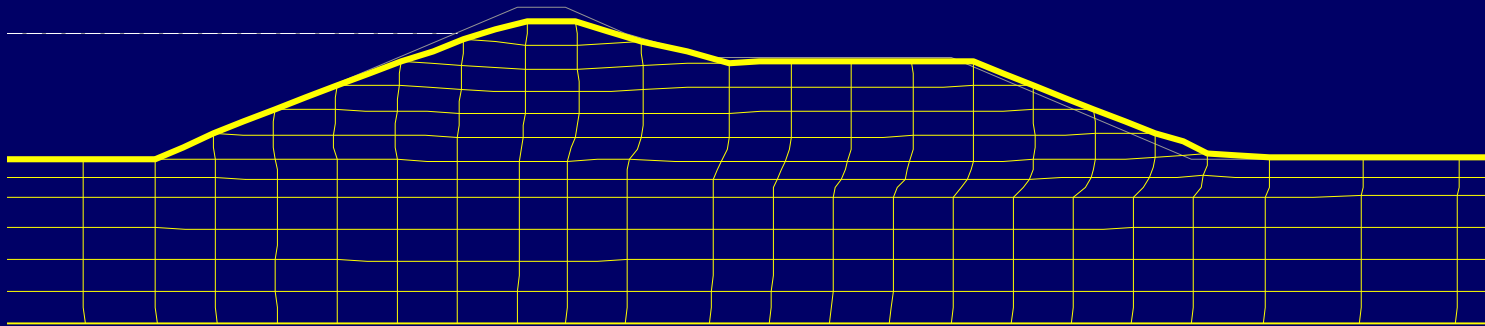
Flow Deformation of the Upper dam  $t = 31$ sec



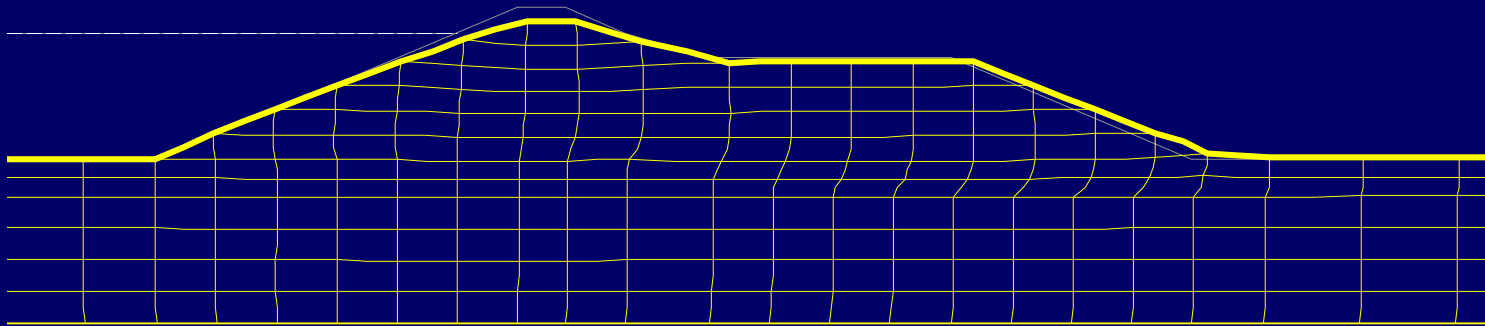
Flow Deformation of the Upper dam  $t = 32$ sec



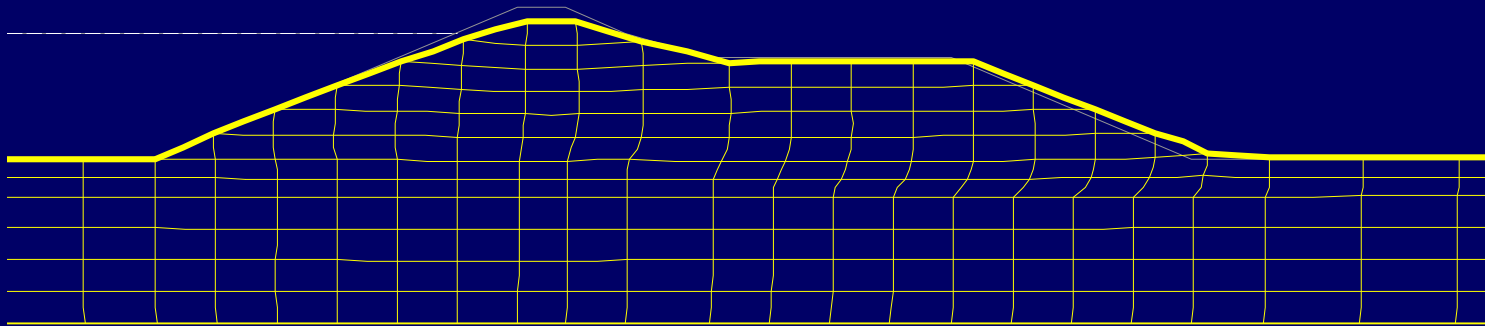
Flow Deformation of the Upper dam  $t = 33$ sec



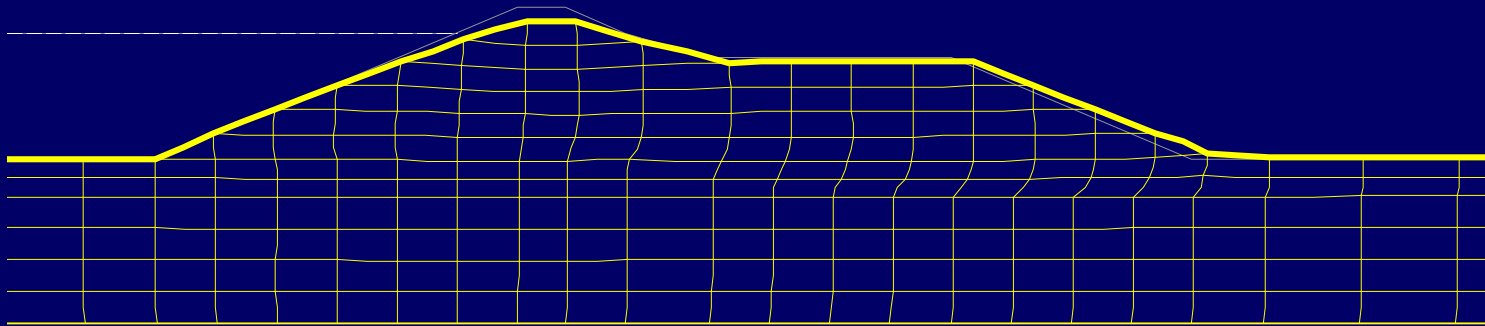
Flow Deformation of the Upper dam  $t = 34$ sec



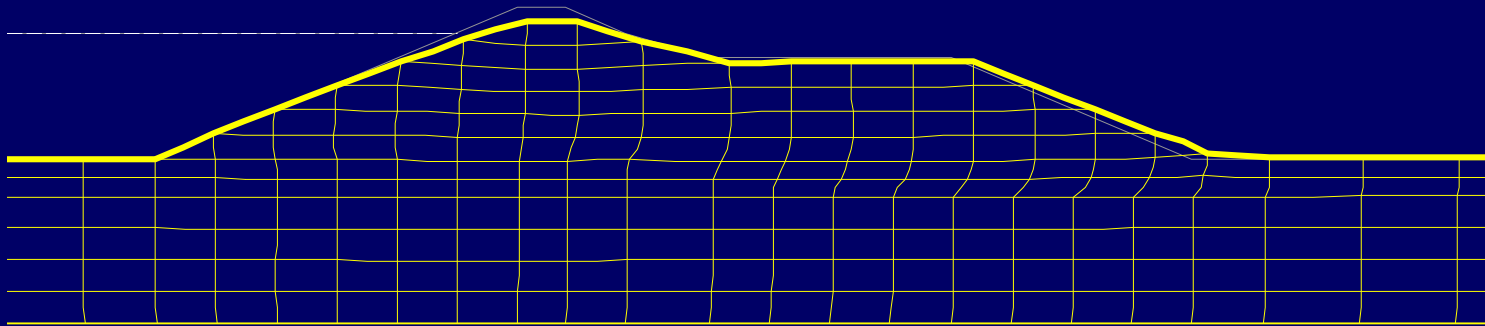
Flow Deformation of the Upper dam  $t = 35$ sec



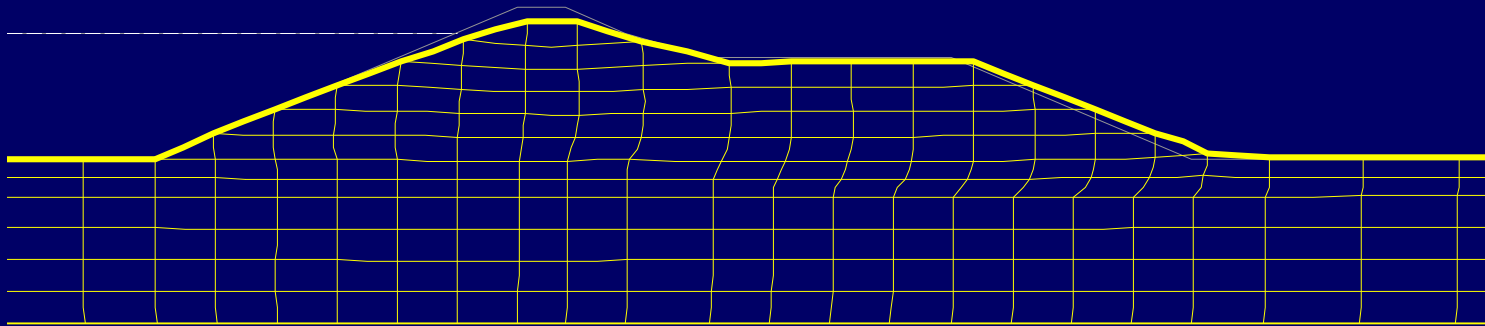
Flow Deformation of the Upper dam  $t = 36$ sec



Flow Deformation of the Upper dam  $t = 37$  sec

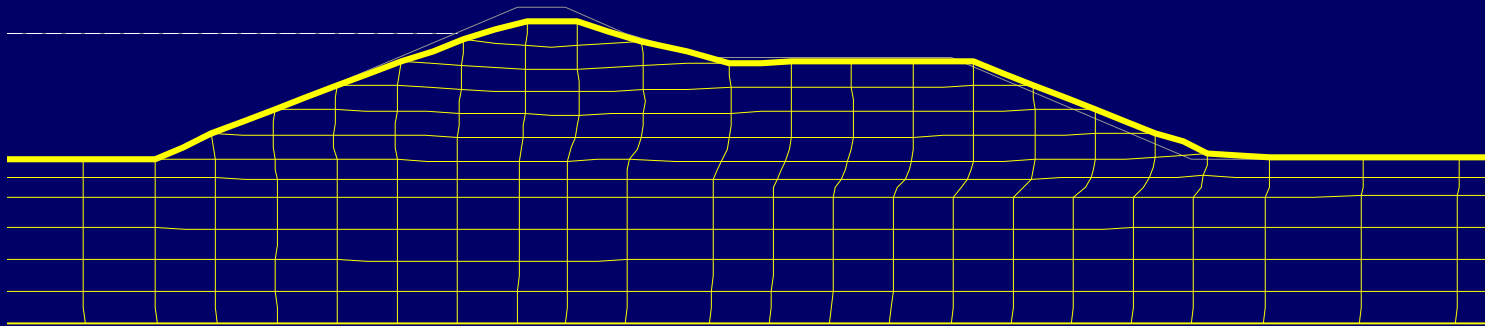


Flow Deformation of the Upper dam  $t = 38$ sec



# Flow Deformation of the Upper dam $t = 39$ sec

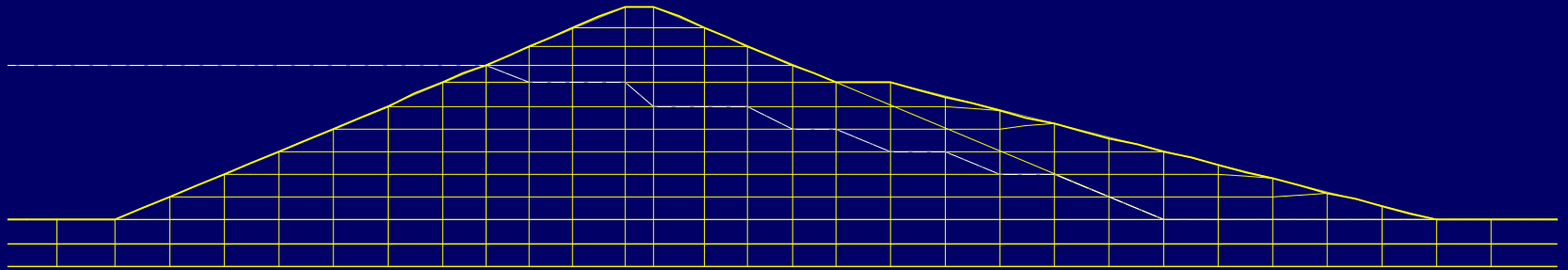
Click on the mesh to return



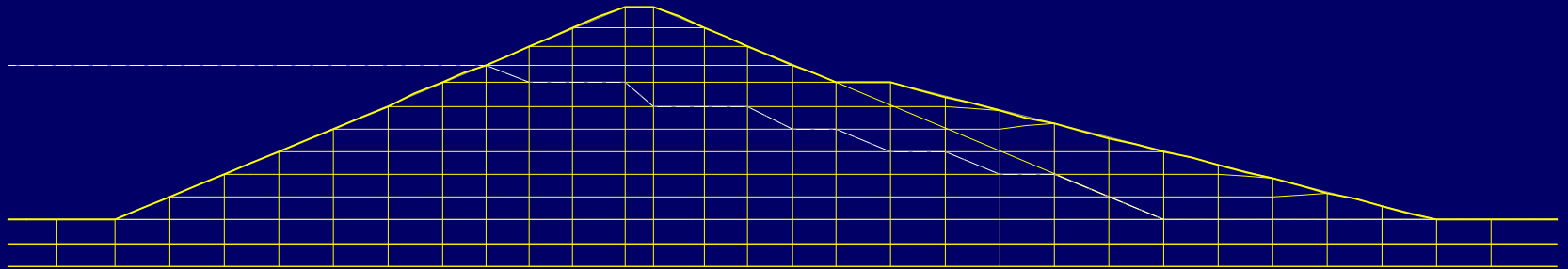
# Animation LSF

- flow failure

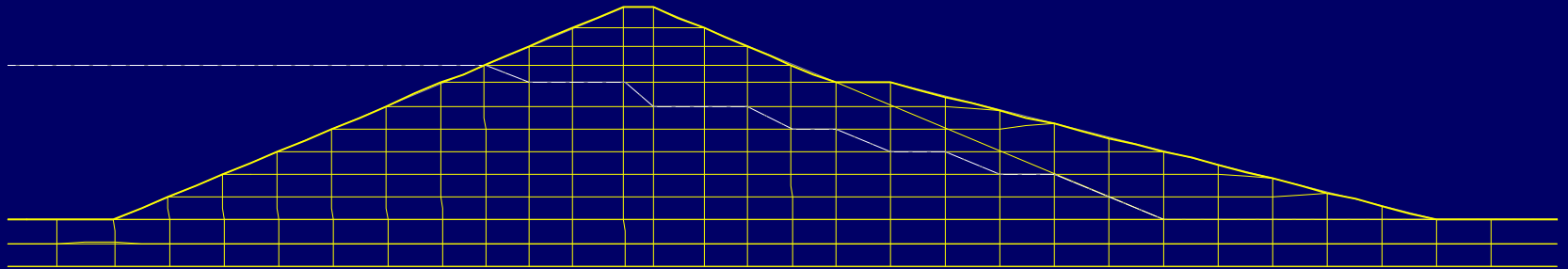
# Flow Failure of the Lower Dam $t = 01$ sec



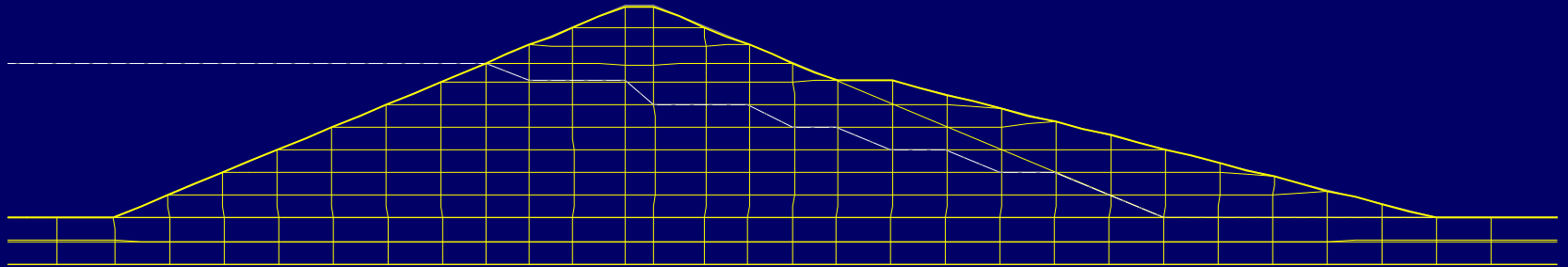
# Flow Failure of the Lower Dam $t = 02$ sec



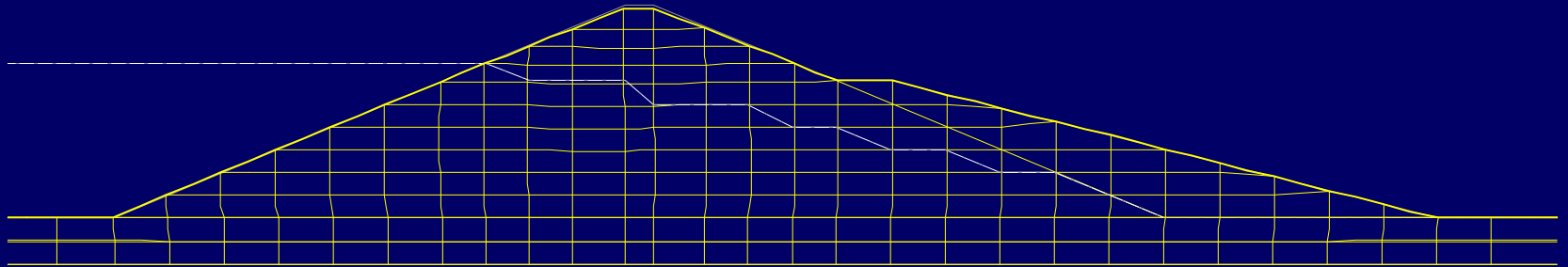
# Flow Failure of the Lower Dam $t = 03$ sec



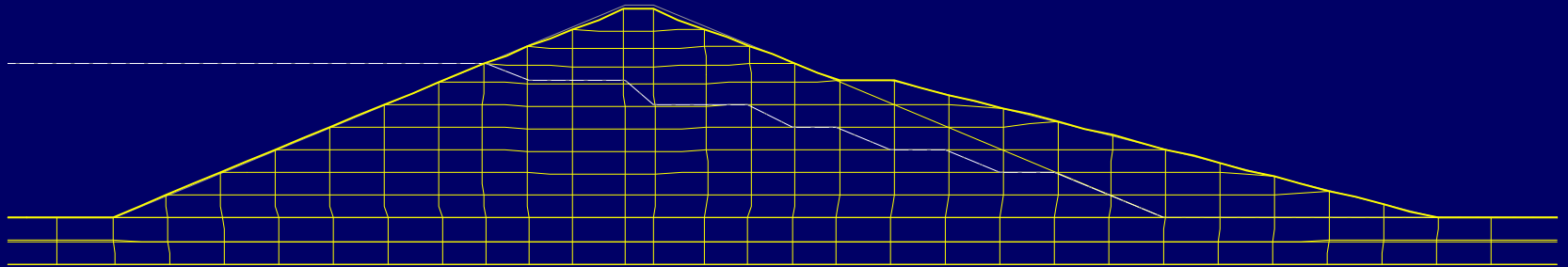
# Flow Failure of the Lower Dam $t = 04$ sec



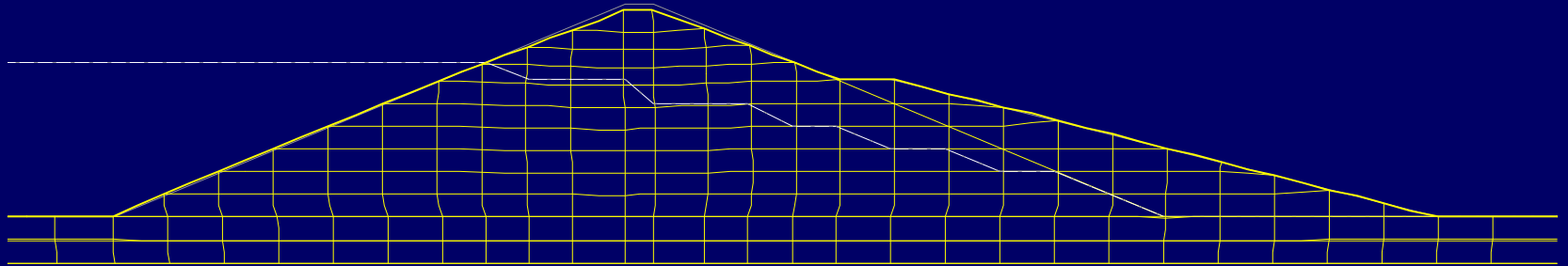
# Flow Failure of the Lower Dam $t = 05$ sec



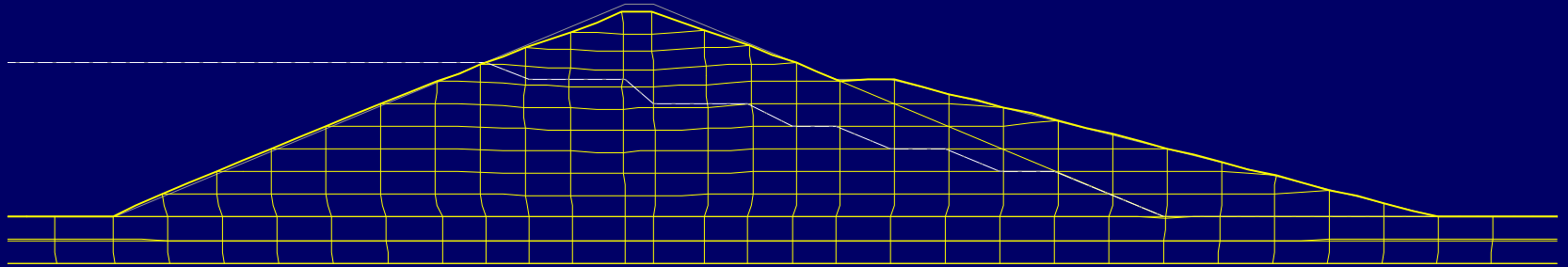
# Flow Failure of the Lower Dam $t = 06$ sec



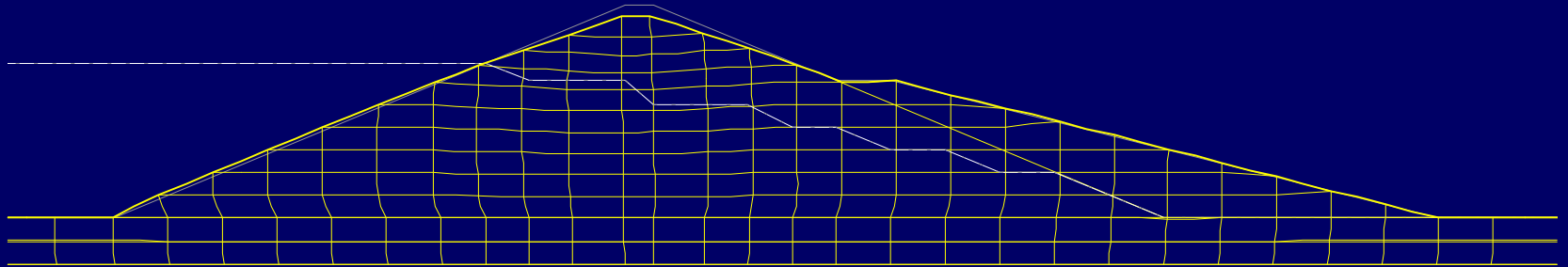
# Flow Failure of the Lower Dam $t = 07$ sec



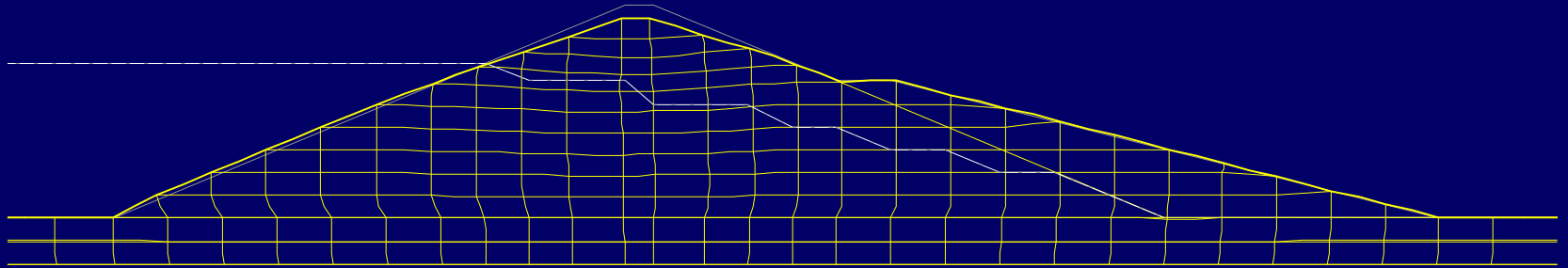
# Flow Failure of the Lower Dam $t = 08$ sec



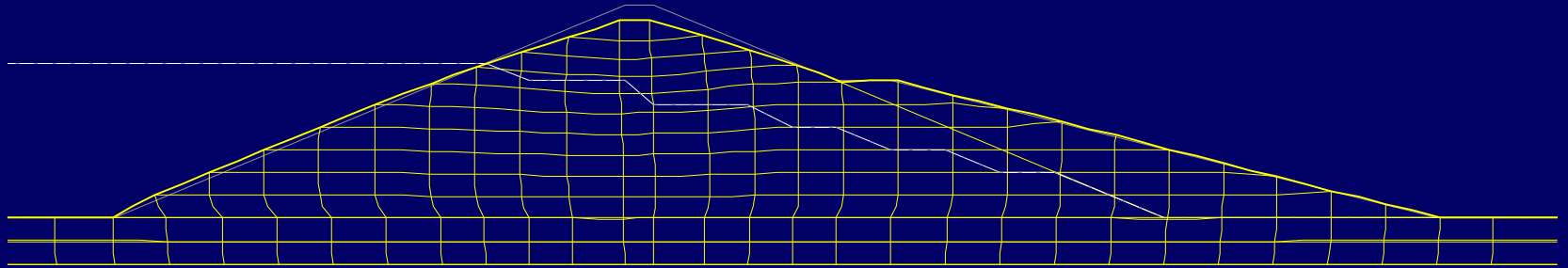
# Flow Failure of the Lower Dam $t = 09$ sec



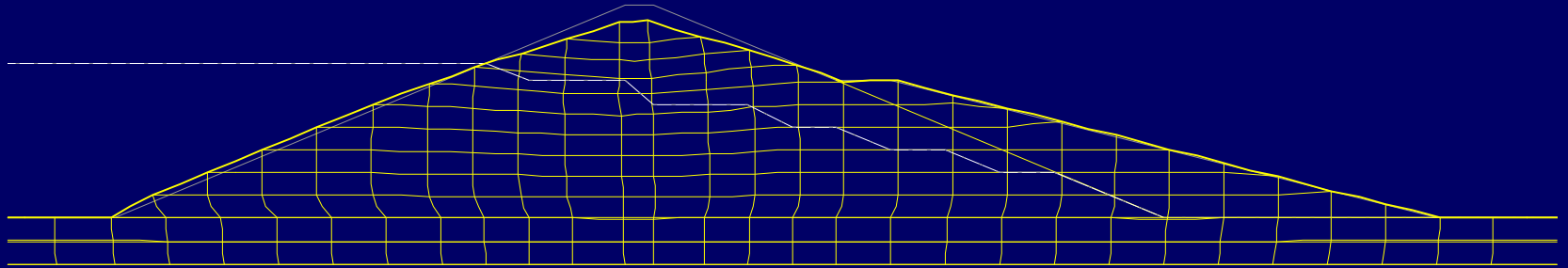
# Flow Failure of the Lower Dam $t = 10$ sec



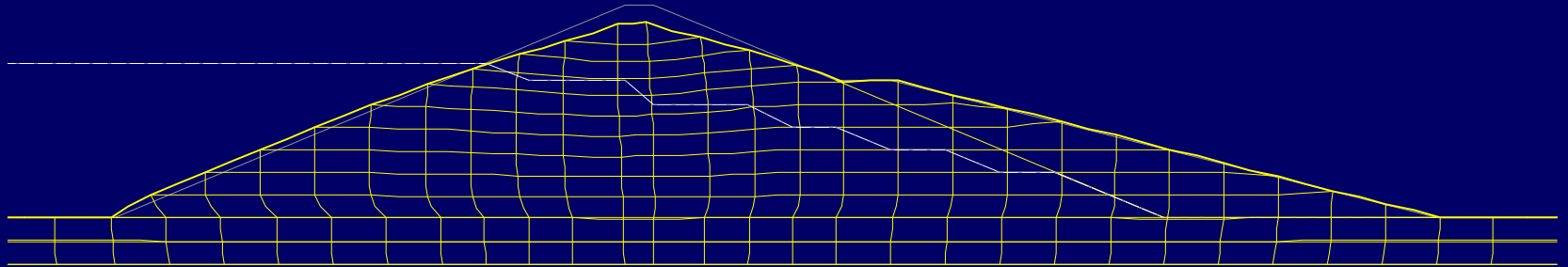
# Flow Failure of the Lower Dam $t = 11$ sec



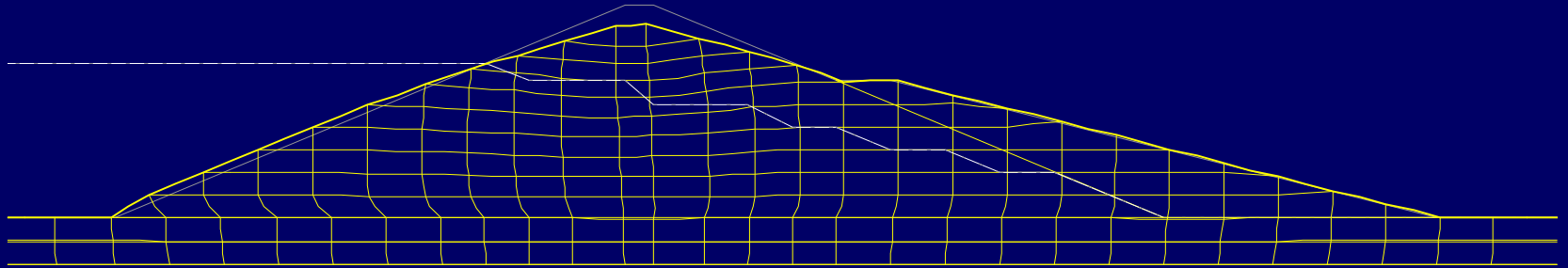
# Flow Failure of the Lower Dam $t = 12$ sec



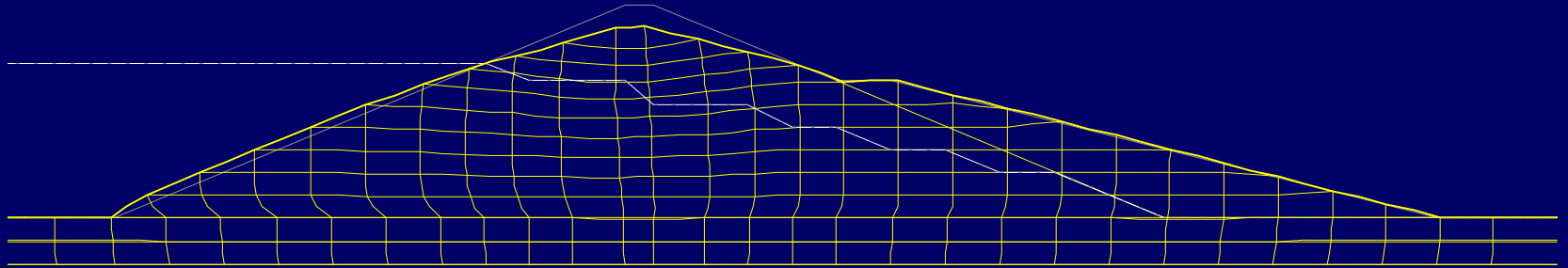
# Flow Failure of the Lower Dam $t = 13$ sec



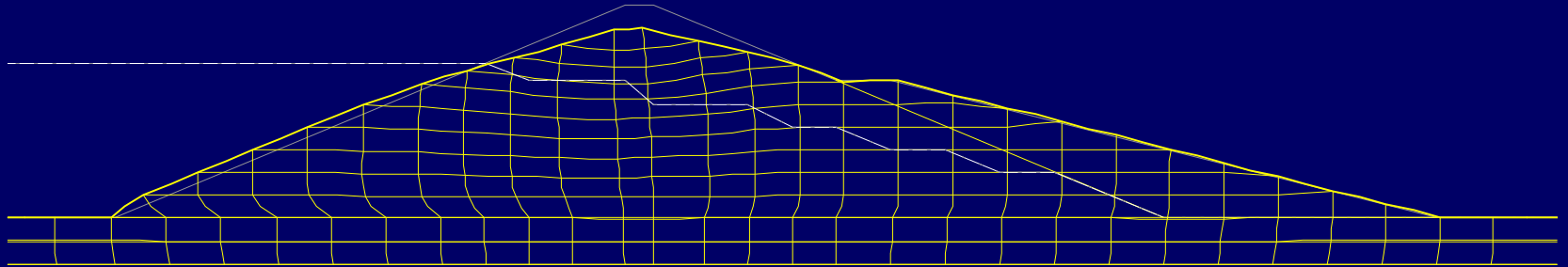
# Flow Failure of the Lower Dam $t = 14$ sec



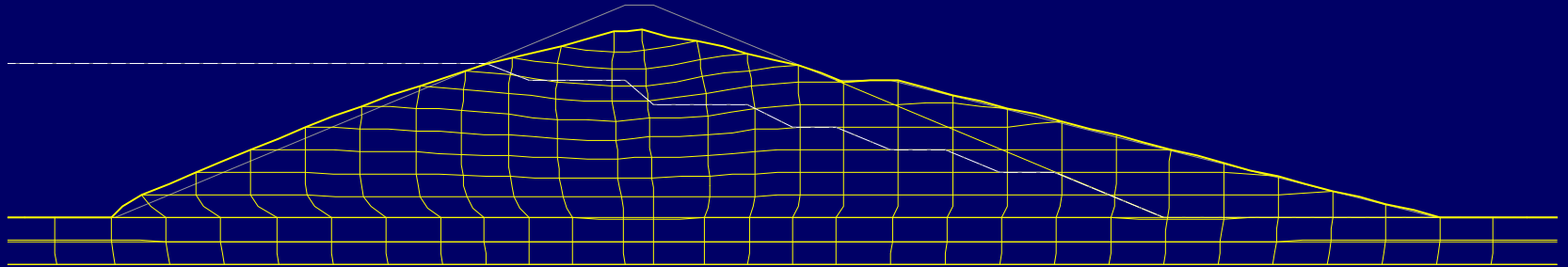
# Flow Failure of the Lower Dam $t = 15$ sec



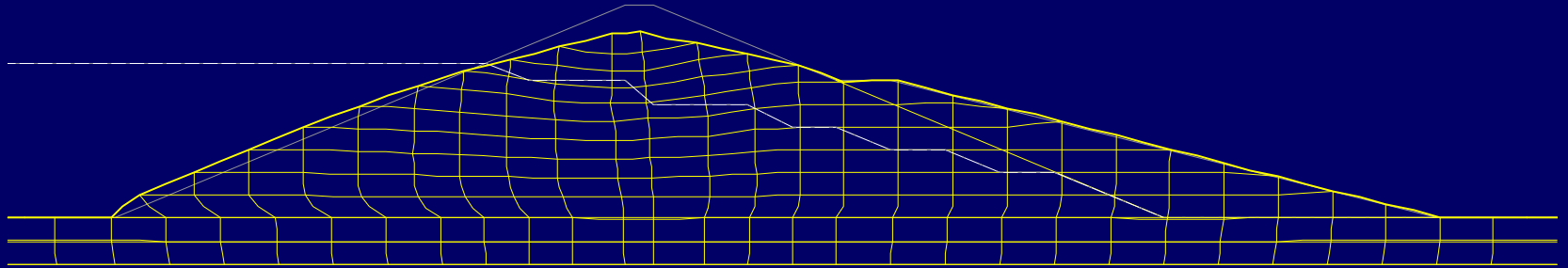
# Flow Failure of the Lower Dam $t = 16$ sec



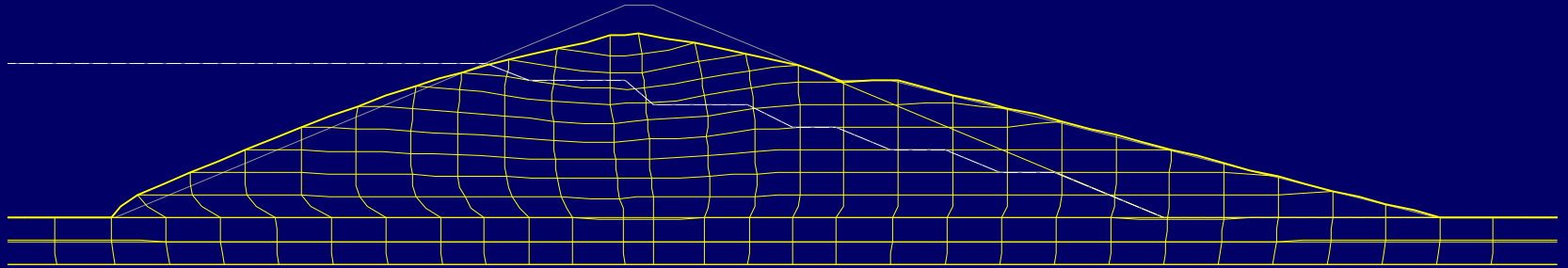
# Flow Failure of the Lower Dam $t = 17$ sec



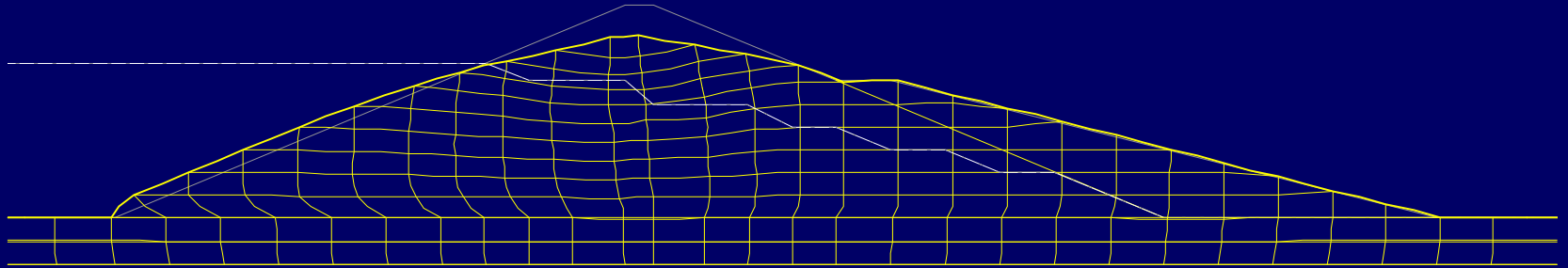
# Flow Failure of the Lower Dam $t = 18$ sec



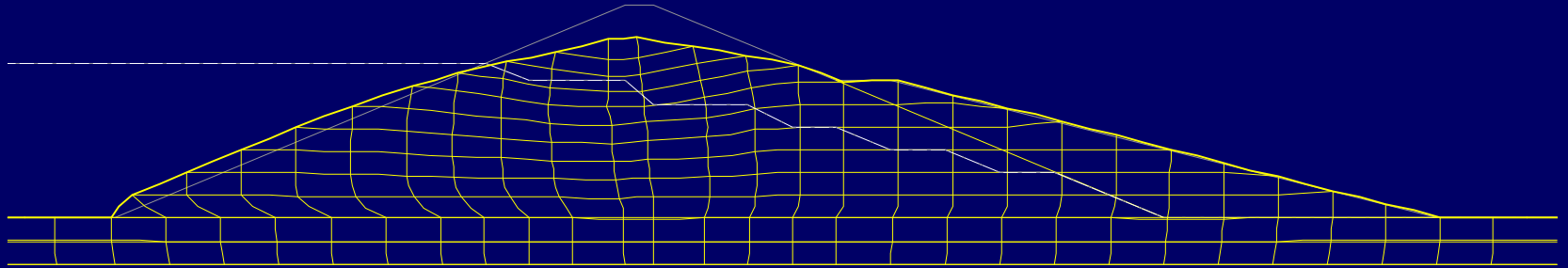
# Flow Failure of the Lower Dam $t = 19$ sec



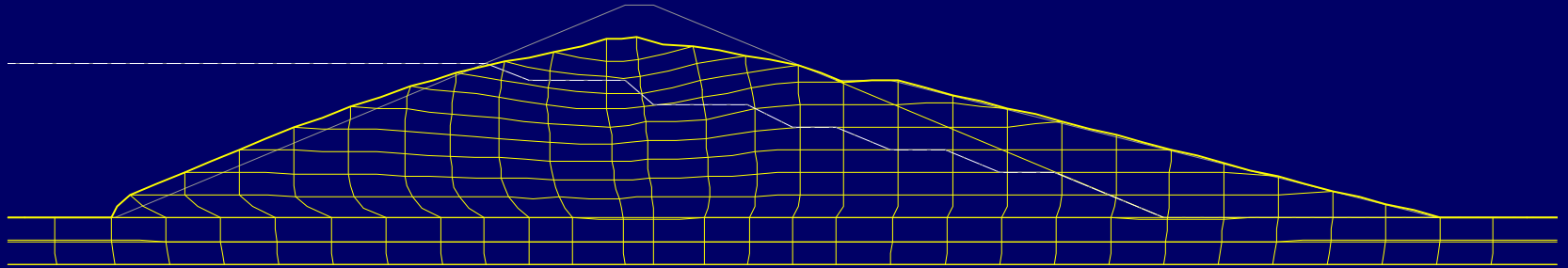
# Flow Failure of the Lower Dam $t = 20$ sec



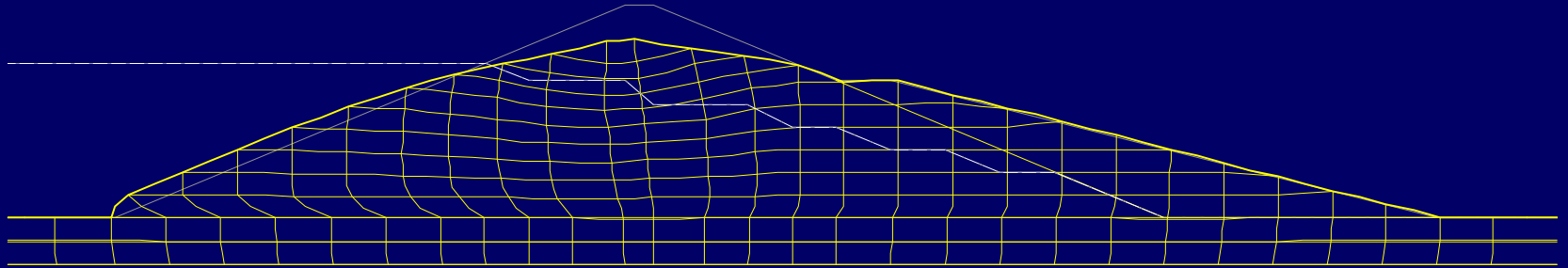
# Flow Failure of the Lower Dam $t = 21$ sec



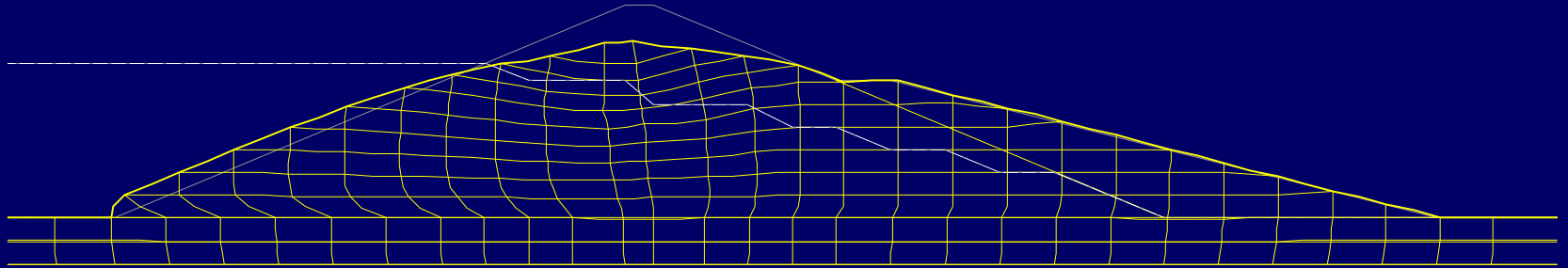
# Flow Failure of the Lower Dam $t = 22$ sec



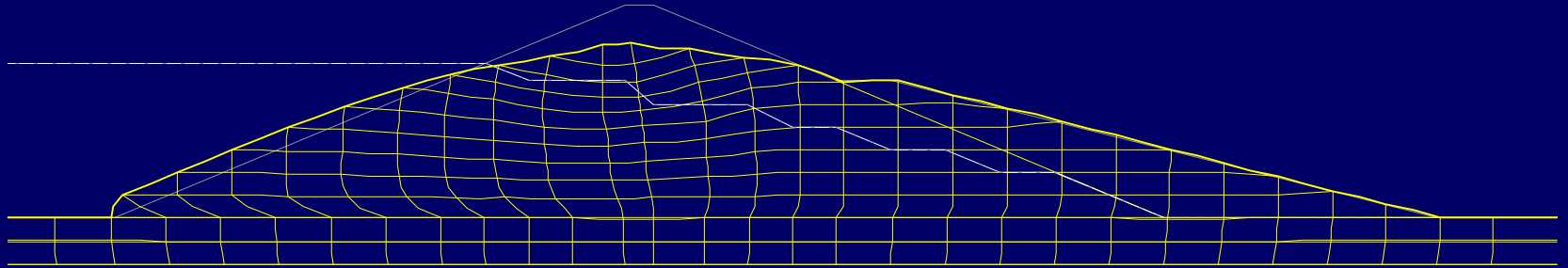
# Flow Failure of the Lower Dam $t = 23$ sec



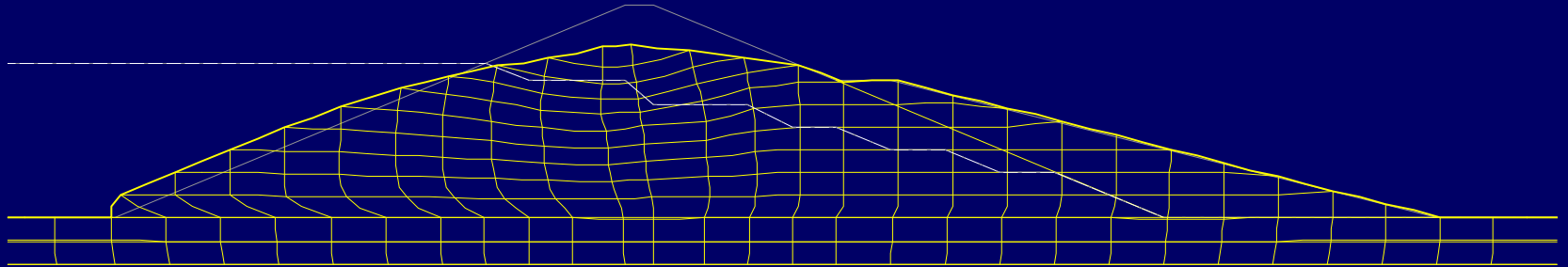
# Flow Failure of the Lower Dam $t = 24$ sec



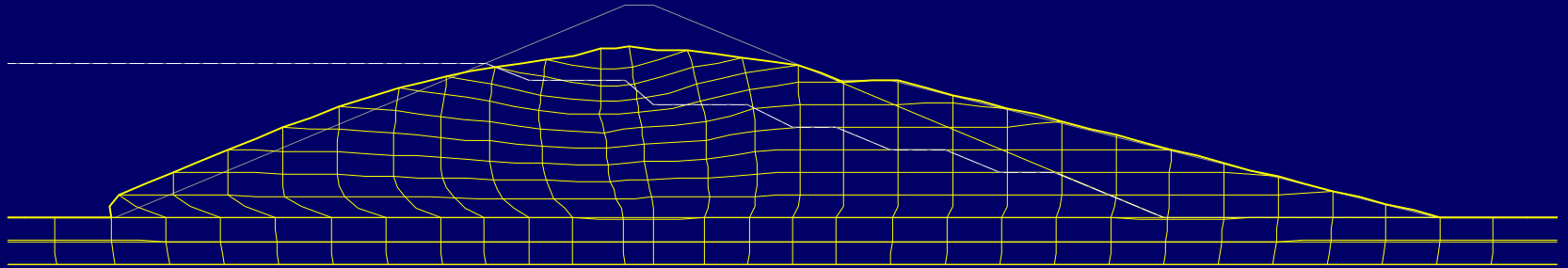
# Flow Failure of the Lower Dam $t = 25$ sec



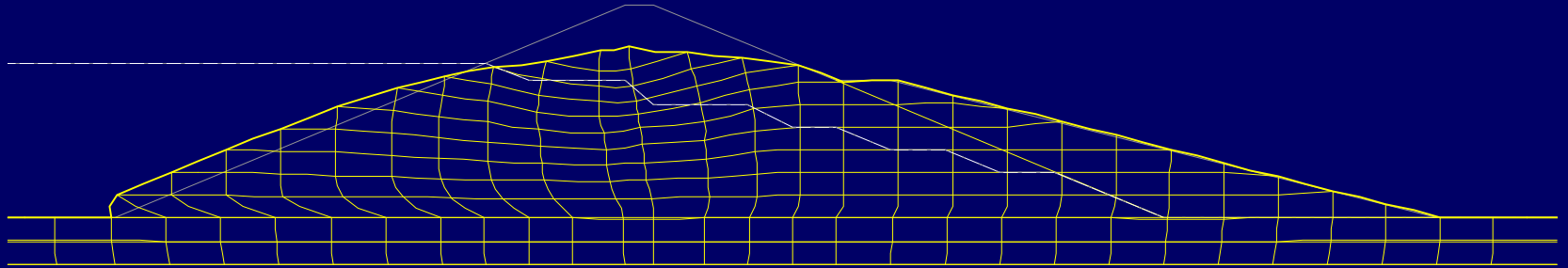
# Flow Failure of the Lower Dam $t = 26$ sec



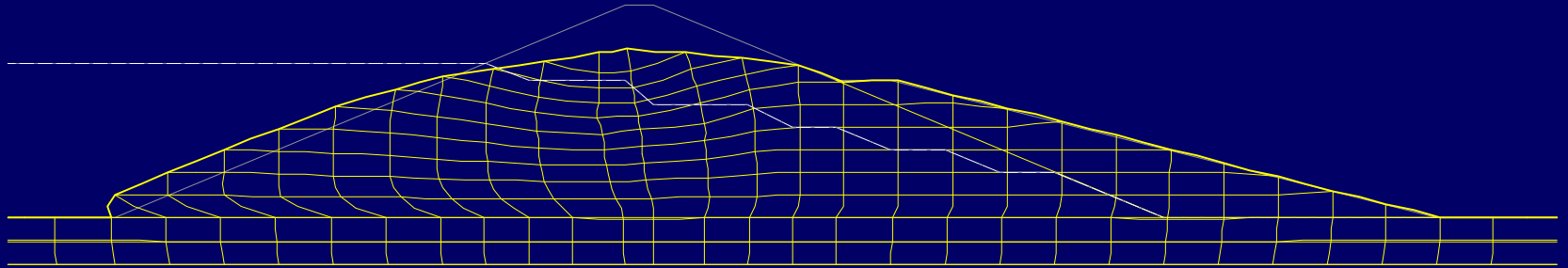
Flow Failure of the Lower Dam  $t = 27$  sec



# Flow Failure of the Lower Dam $t = 28$ sec



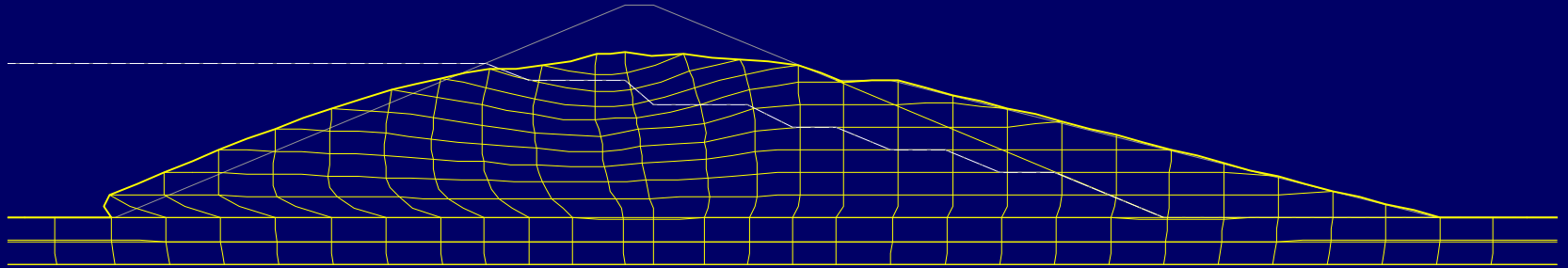
# Flow Failure of the Lower Dam $t = 29$ sec



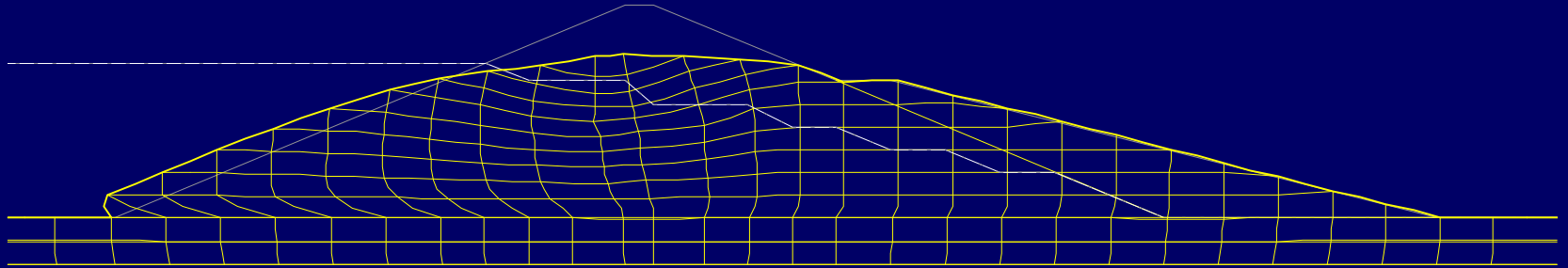
# Flow Failure of the Lower Dam $t = 30$ sec



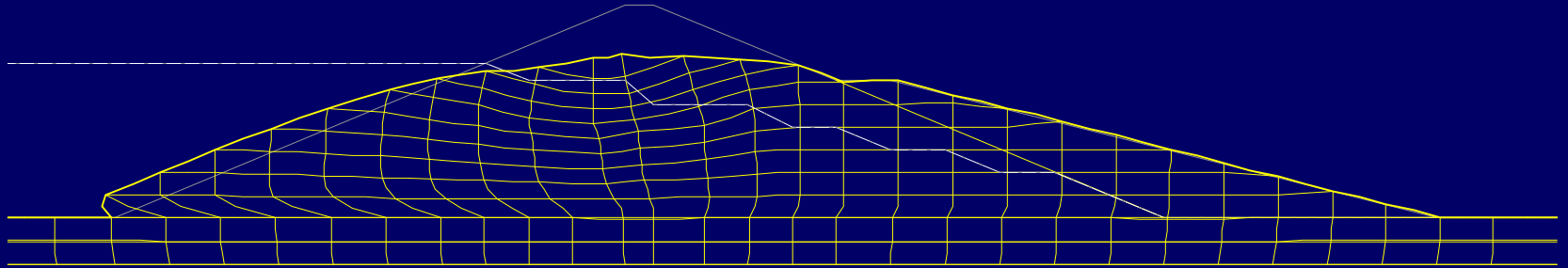
# Flow Failure of the Lower Dam $t = 31$ sec



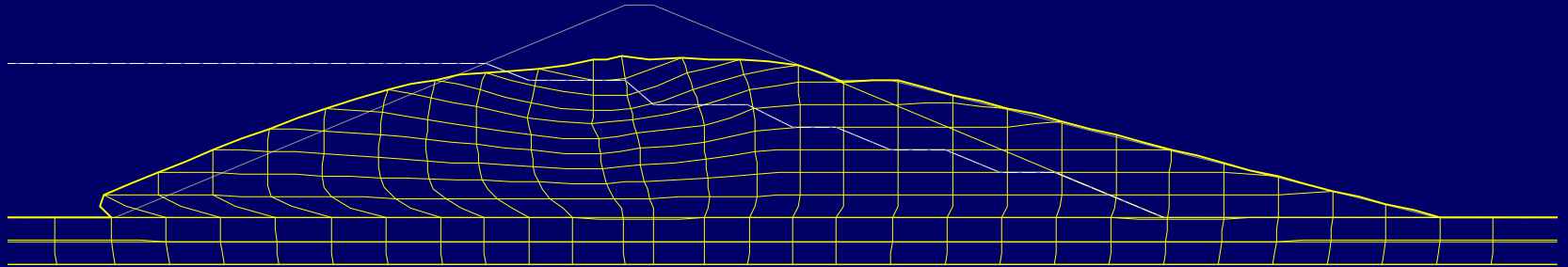
# Flow Failure of the Lower Dam $t = 32$ sec



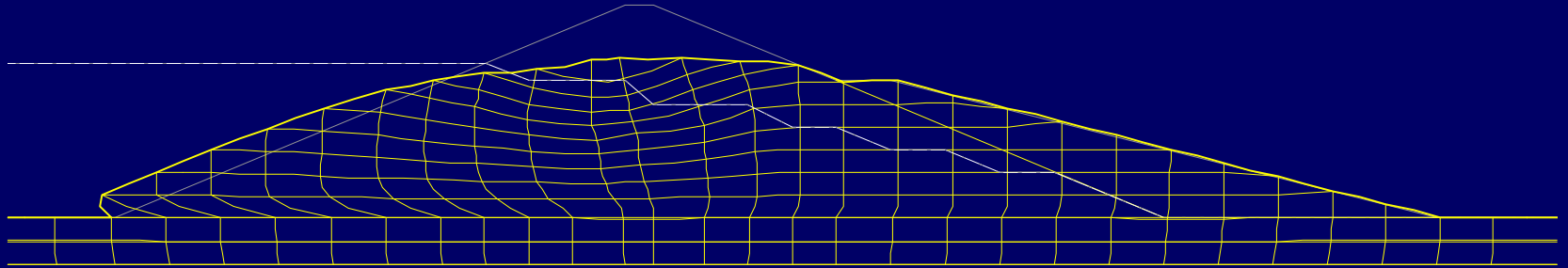
# Flow Failure of the Lower Dam $t = 33$ sec



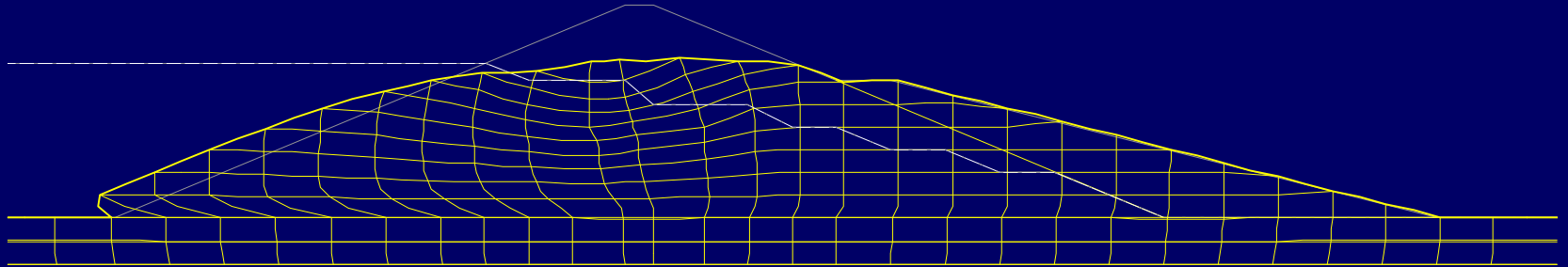
# Flow Failure of the Lower Dam t = 34sec



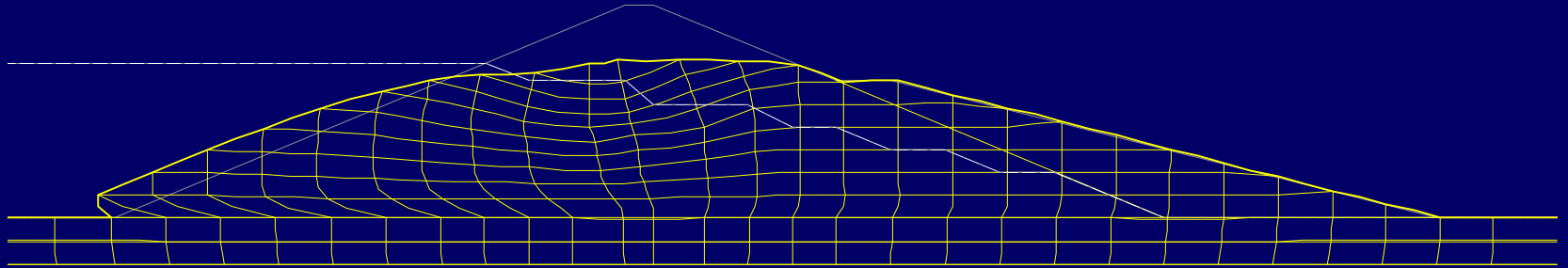
# Flow Failure of the Lower Dam $t = 35$ sec



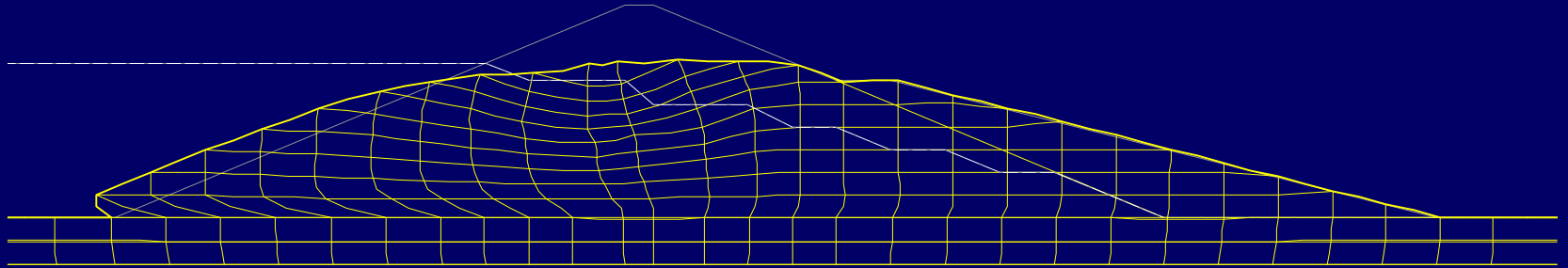
# Flow Failure of the Lower Dam t = 36sec



Flow Failure of the Lower Dam  $t = 37$  sec



Flow Failure of the Lower Dam  $t = 38$ sec



# Flow Failure of the Lower Dam t = 39sec

Click on the mesh to return

