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MILANO
Numerical analysis of dams

ICOLD COMMITTEE ON COMPUTATIONAL ASPECTS OF ANALYSIS AND DESIGN OF DAMS

15th INTERNATIONAL BENCHMARK WORKSHOP ON NUMERICAL ANALYSIS OF DAMS

Theme A - Formulation

SEISMIC ANALYSIS OF PINE FLAT CONCRETE DAM

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Investigation of Free-Field Effects

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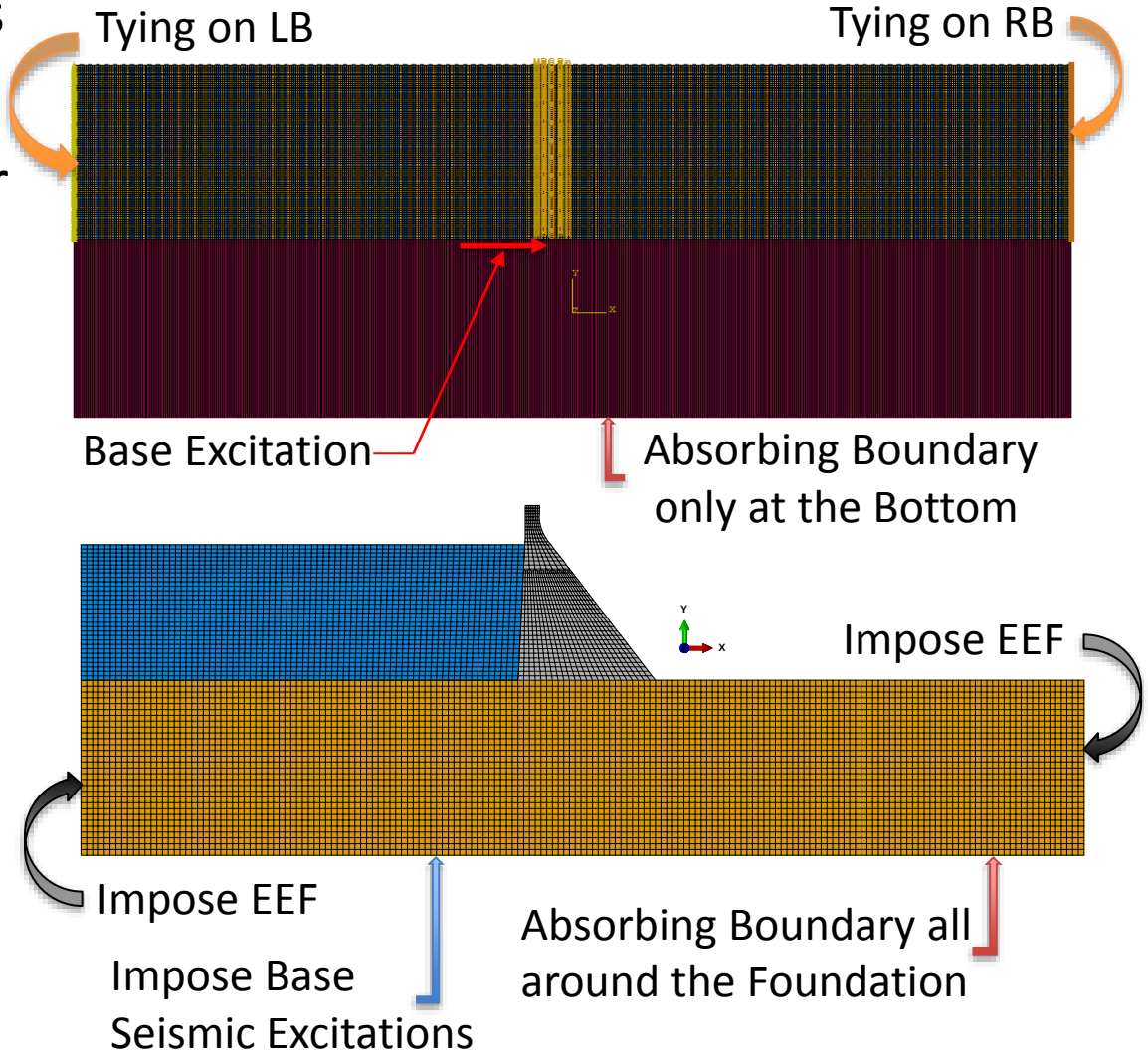
Scope of Presentation

- The main aim of this presentation is to compare results obtained for two Cases B & D with and without inclusion of the Free-Field Boundary (FFB) effects
- Free-field boundary conditions must be imposed in analytical models using foundation with mass, in addition to non-reflecting or absorbing boundaries

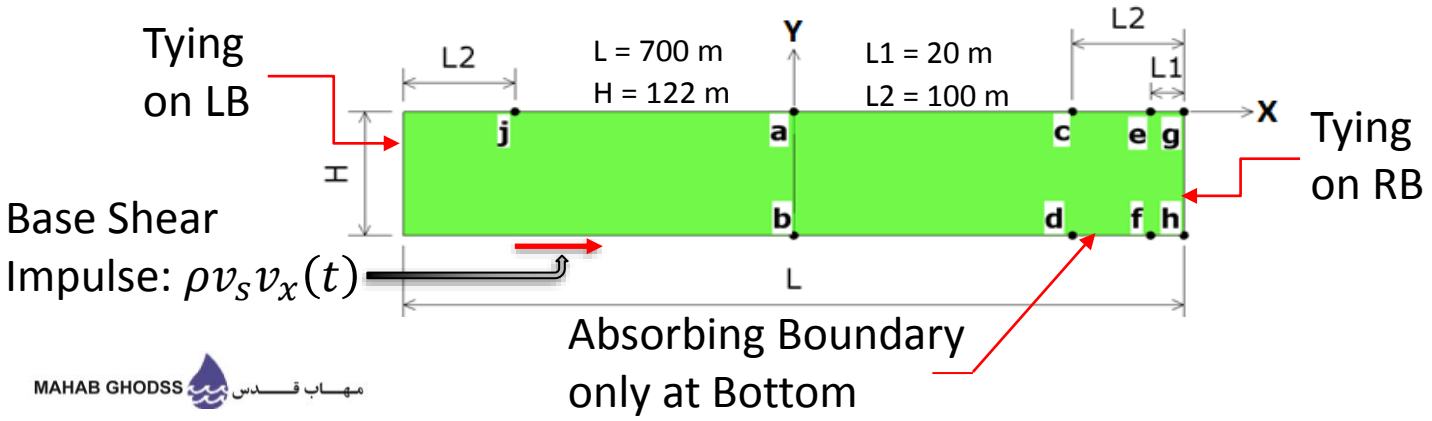
Analytical Approaches

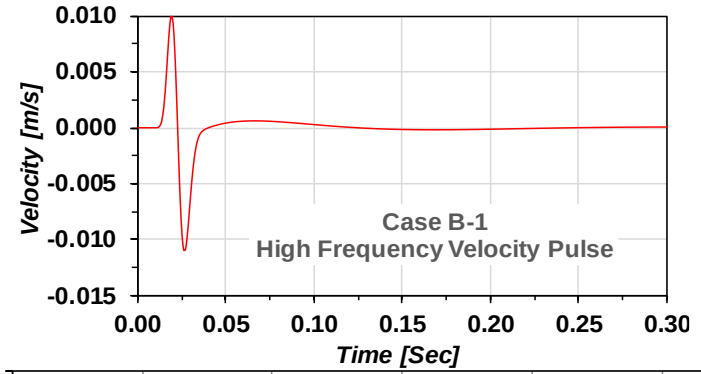
- Particular (1st) approach for imposition of FFB is nodal constraining (tying) of lateral boundaries
- Tying is applicable for models with symmetry or sufficiently large spacing of vertical boundaries
- In case of earthquake, general (2nd) approach is the calculation and imposition of Effective Earthquake Forces (EEF) on vertical sides
- To find EEF, free-field motions (u & $\dot{u}$) at each nodal point along vertical sides must be found
- Two models are studied. The 1st one for Case B with tying constraints. The 2nd one for Case D with imposed EEF

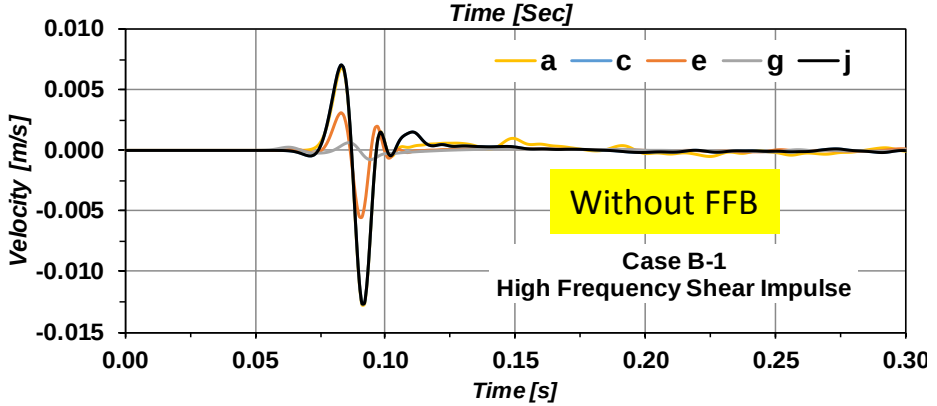


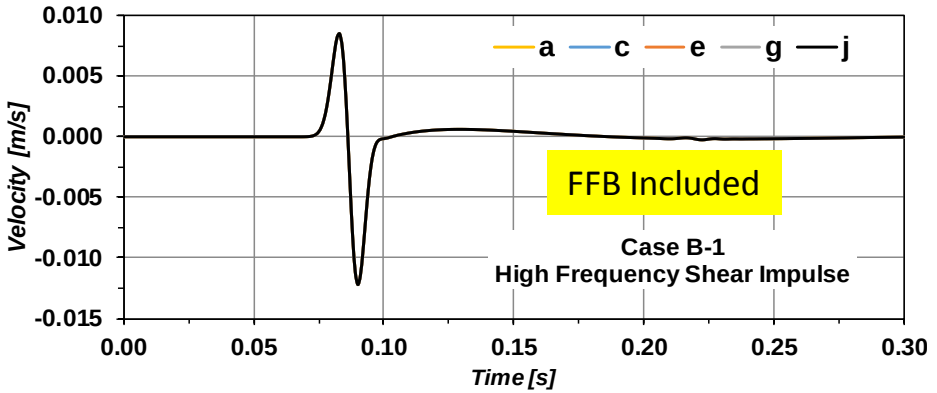
Particular Approach: Constraining of Nodes

- Displacement of pair of nodal points positioned on lateral boundaries are constrained together
- Tying (coupling) is defined for both X & Y components
- Without FFB and only absorbing elements all around, amplitude of pulses are reduced unrealistically by getting close to the boundary (points c, e & g)
- With FFB included and absorbing elements **only** at the bottom, responses of all top points are identical
- Same also governs at base points (b, d, f & h)



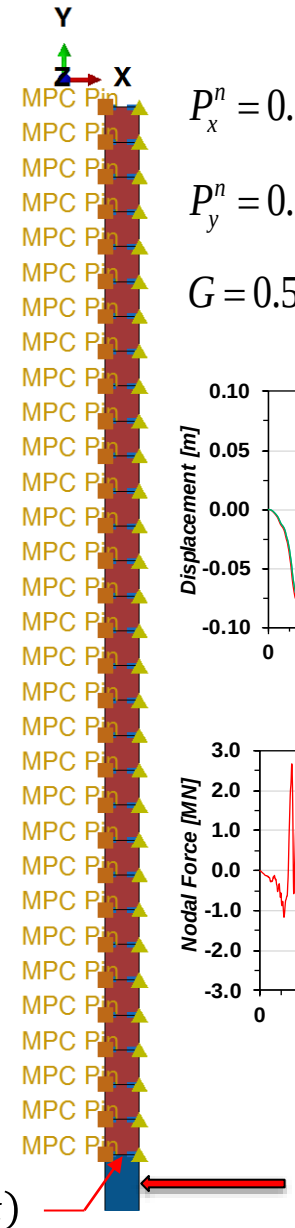






General Approach: Calculation of EEF

- Analysis starts with a single column of the foundation-rock with absorbing infinite elements only at the base
- Pair of nodes positioned on both sides of the rock-column are constrained
- Mesh density of the rock-column is identical to main model (Case D)
- Rayleigh viscous damping is included
- With only Taft Shear Traction imposed at the base, evidently $u_y = \dot{u}_y = 0$
- P_x^n on both sides are identical and in same direction at each time step
- P_y^n are equal on sides but opposite



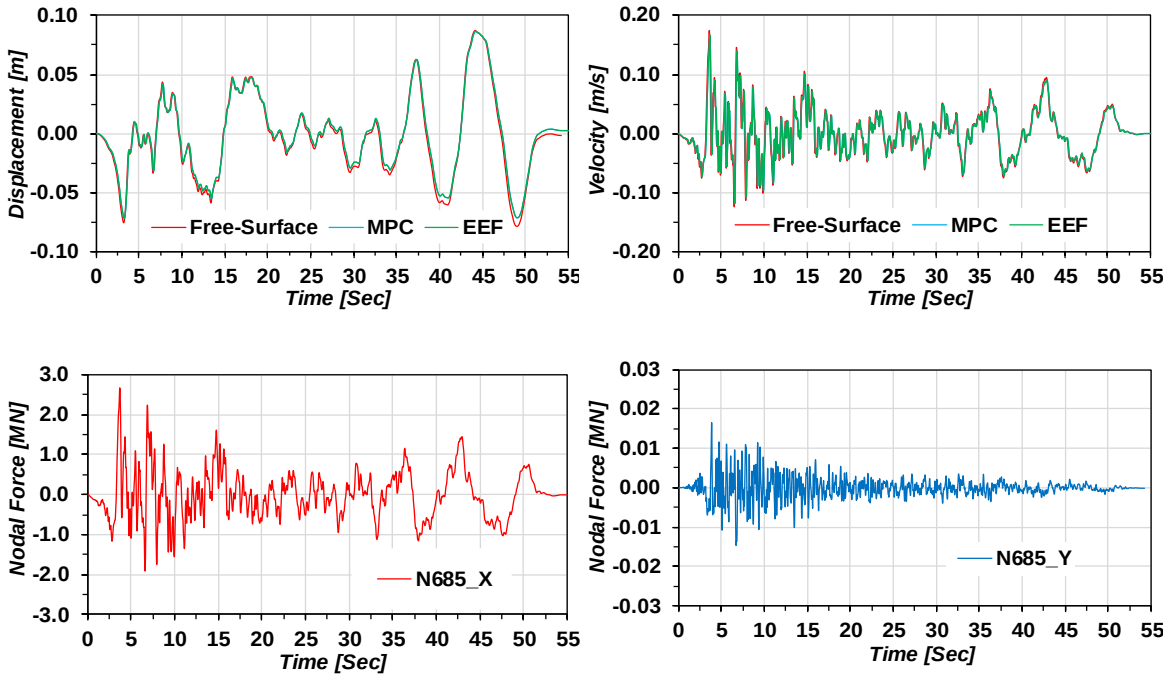
Taft Base Shear Traction: $\rho v_s v_x(t)$

Absorbing Infinite Element (Truncated for Illustration)

$$P_x^n = 0.5\left[h\rho c_p \dot{u}_x^n + l_x\lambda\left(u_y^{n+1} - u_y^n\right)\right], \quad P_x^{n+1} = 0.5\left[h\rho c_p \dot{u}_x^{n+1} + l_x\lambda\left(u_y^{n+1} - u_y^n\right)\right]$$

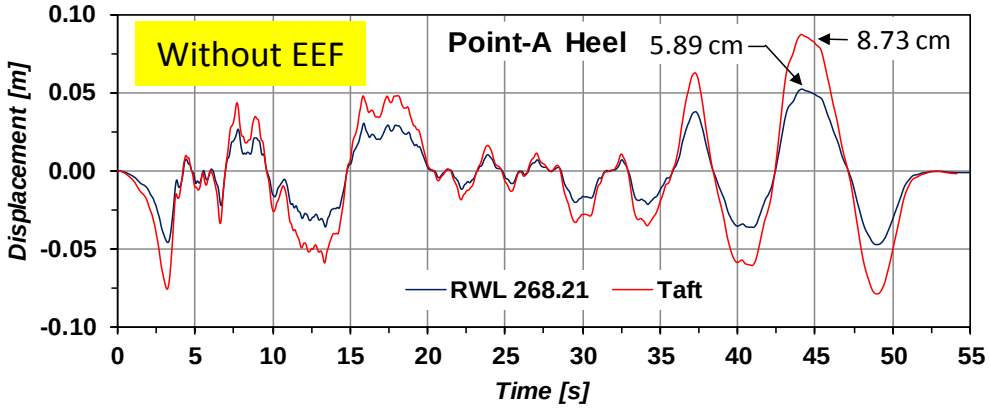
$$P_y^n = 0.5\left[h\rho c_s \dot{u}_y^n + l_x G\left(u_x^{n+1} - u_x^n\right)\right], \quad P_y^{n+1} = 0.5\left[h\rho c_s \dot{u}_y^{n+1} + l_x G\left(u_x^{n+1} - u_x^n\right)\right]$$

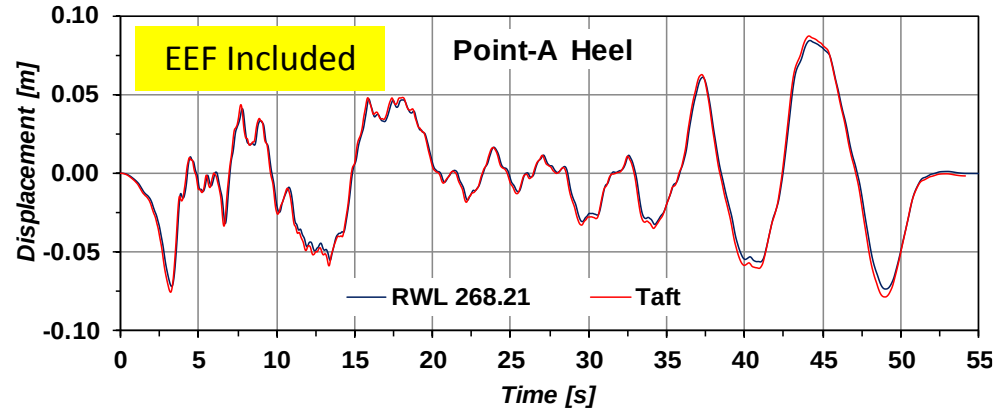
$$G = 0.5E/(1+\nu), \quad \lambda = 2G\nu/(1-2\nu), \quad c_p = \sqrt{(\lambda+2G)/\rho}, \quad c_s = \sqrt{G/\rho}$$

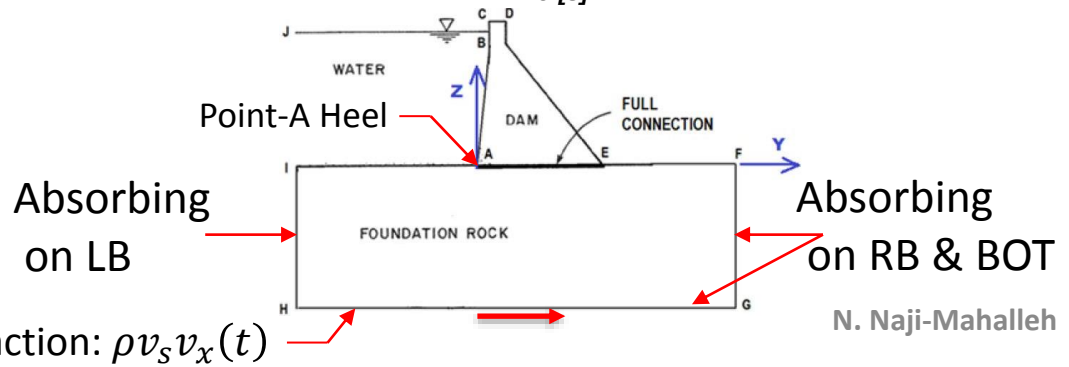


Effects of EEF on Calculated Displacements

- EEF extracted from a single rock-column is superimposed in a dynamic step (Case D)
- Without EEF, maximum response difference at A & Taft free-surface record is about 33%
- With EEF included, displacement (u_x) at heel point (A) almost fits free-surface displacement of the Taft record
- Same also governs for $\dot{u}_x$ and $\ddot{u}_x$ reponses
- **Note**: On the graphs the initial displacement due to static loading is excluded
- **Hint**: With only horizontal excitation, free-field fluid-column is not necessary to be employed



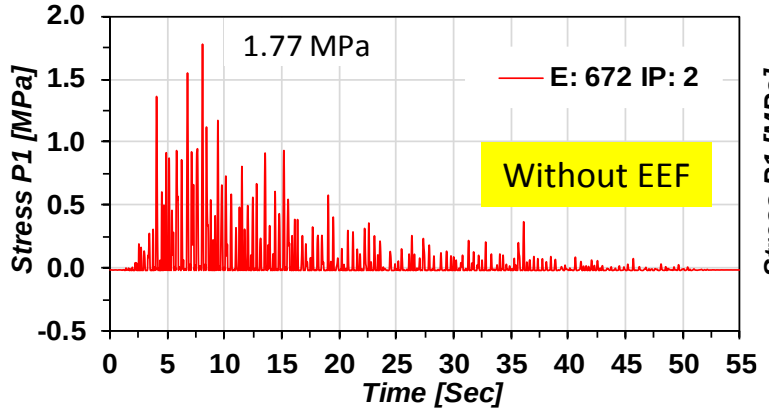


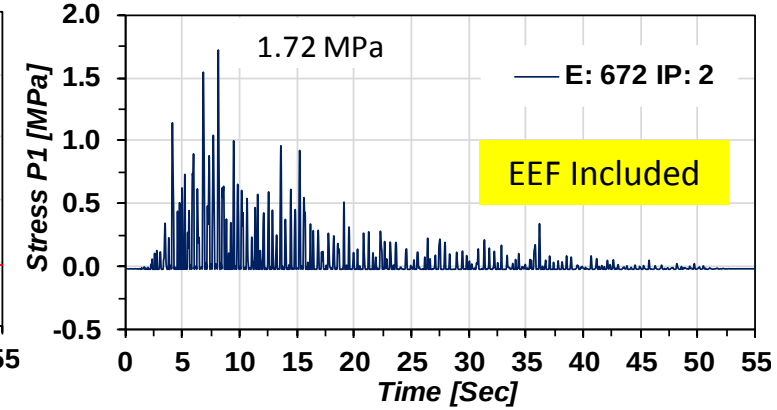


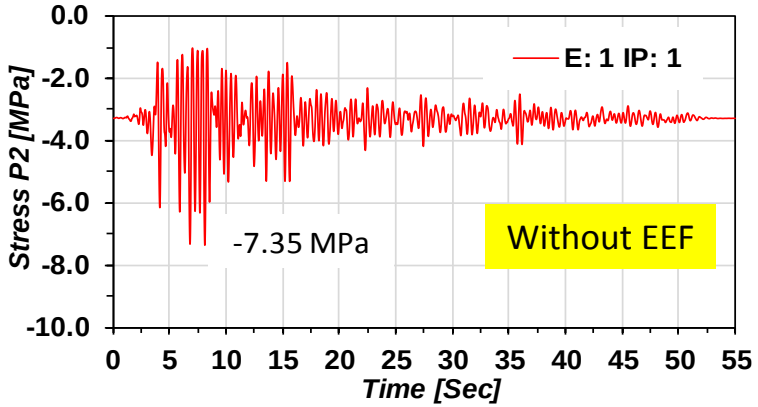
Taft Base Shear Traction: $\rho v_s v_x(t)$

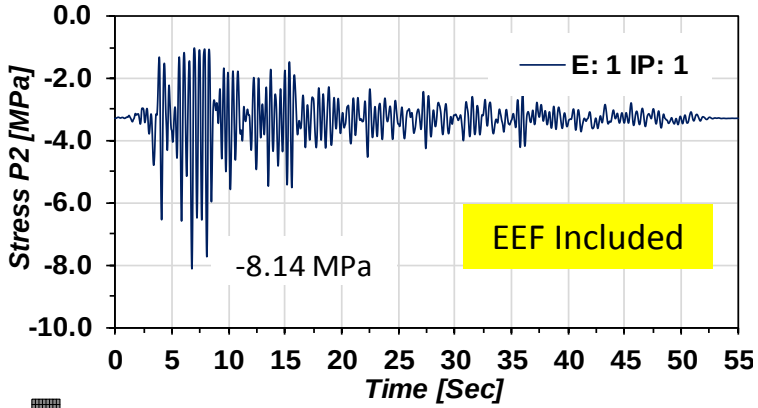
Effects of EEF on Calculated Stresses

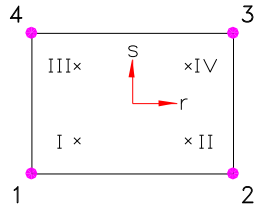
- Responses are submitted for two elements that are located at areas with high stress concentration (Case E)
- Principal stresses are given at Gauss Integration points
- With EEF included:
  - Maximum principal stress (p1) is reduced by 3% at top
  - Minimum principal stress (p2) is increased by 10% at heel



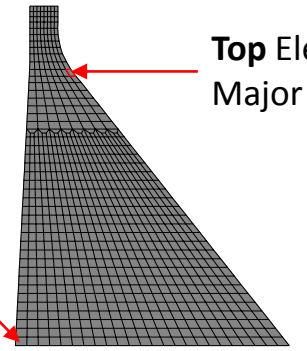








HEEL Element No. 1
Major Crushing Zone



Top Element No. 672
Major Cracking Zone

Final Remarks on Presentation

- Inclusion of free-field boundary effects leads to realistic results
- In 2D analysis, computation of EEF by rock-column approach is straightforward and is not a heavy task as it seems to be

Remarks on 15th BMW Theme A

- In future Benchmarks, extension of the present Theme (foundation with mass) for 3D seismic analysis of the arch dams is recommended.