ICOLD
INTERNATIONAL
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LARGE 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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SEISMIC ANALYSIS OF PINE FLAT CONCRETE DAM

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- Introduction
- Dam geometry and modelling
- CaseA – EMVG Test Simulation
- CaseC – Dynamic analysis using impulsive loads
- CaseD – Dynamic analysis for various reservoir levels
- CaseE – Non-linear dynamic analysis
- Conclusions

Introduction

- Theme A - case study of the seismic response of Pine Flat Dam at action of various earthquake excitations - total of 8 case studies formulated
  - Case A – EMVG Test Simulation (Simulation of the eccentric-mass vibration generator (EMVG) performed at Pine Flat Dam in 1971)
  - Case B – Foundation Analysis using Impulsive Loads (Investigate the effect of foundation size and analyze the efficiency of non-reflecting boundary conditions in the dynamic analysis of dams - Impulsive Stress Records)
  - Case C – Dynamic Analysis using Impulsive Loads (Case B, which considers only the foundation, is extended to include the dam and reservoir - Impulsive Stress Records)
  - Case D – Dynamic Analysis for Various Reservoir Levels (Investigate the effect of water levels. The dam-reservoir-foundation model defined in Case C is analyzed for various reservoir water levels and Taft Record)
  - Case E – Non-linear Dynamic Analysis (Investigate the effect of nonlinear behavior of the dam. The dam-reservoir-foundation model defined for Case D is extended to include nonlinear properties for concrete -Taft and ETAF)
  - Case F – Massless Foundation (Investigate the effect of using a massless foundation. The dam-reservoir-foundation model defined for Case D is modified to use a massless foundation. Analyses will use the Taft Record).

Dam geometry and modelling

- **Discretization of dam body and foundation by finite elements**
  - 3D model - 1m' length in X-direction - approximated plane analysis.
  - Generally - discretization of dam body and rock foundation - applied quadrilateral finite element (auxiliary elements, quad, 4 nodes), volume finite element (bric, 8 nodes) and interface element (dampers and water bedding) type spring.
- **Numerical model**
  - The model - composed of dam body, rock foundation and water fluid (compressible).
  - The model - geometric boundaries - limited to horizontal and vertical plane - defined boundary conditions - varying for various Cases.
- **Dam loading**
- Static load - weight of concrete dam and reservoir without weight of foundation block.
- The applied water loading - 3 reservoir levels: (a) winter reservoir water level at El. 268.21 m; (b) summer reservoir water level at El. 278.57 m and (c) normal reservoir level at El. 290.00 m.

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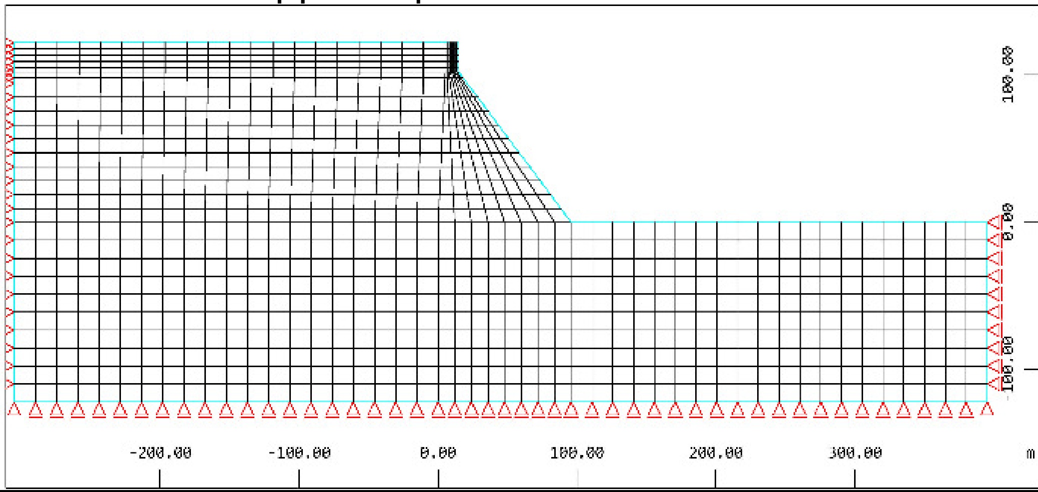

Figure 3: Display of coarse finite element mesh (N=816), applied for CaseA, CaseD, CaseE and Case F.

- The applied water loading - 3 reservoir levels: (a) winter reservoir water level at El. 268.21 m; (b) summer reservoir water level at El. 278.57 m and (c) normal reservoir level at El. 290.00 m.

CaseA – EMVG Test Simulation

- Case A - dynamic linear analysis of the dam-foundation-reservoir system for the harmonic force record exerted by an eccentric-mass vibration generator positioned at the dam crest.
- Boundary conditions: the horizontal edge in the lowest zone of the model is adopted as non-deformable boundary condition by fixed displacements in XYZ direction, the vertical planes perpendicular on X-axis are boundary condition by applying fixed (zero) displacements in X-direction and the vertical planes perpendicular on Y-axis are boundary condition by applying fixed (zero) displacements in Y-direction.
- Input parameters for concrete and rock - elastic.
- During analysis - static weight of the foundation not included.
- Dynamic load - EMVG harmonic-force time history record applied at the middle of the dam crest in the upstream/downstream direction.

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Table 2: Natural frequencies for first 6 modes.

Water level [m]	1st Mode (dam and reservoir)	2nd Mode (dam and reservoir)	3rd Mode (dam and reservoir)	4th Mode (dam and reservoir)	5th Mode (dam and reservoir)	6th Mode (dam and reservoir)
268.21	1.49	2.39	3.09	3.17	3.56	4.18
278.57	1.41	2.32	2.79	3.15	3.28	4.02

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- During analysis - static weight of the foundation not included.
- Dynamic load - EMVG harmonic-force time history record applied at the middle of the dam crest in the upstream/downstream direction.

CaseA – EMVG Test Simulation

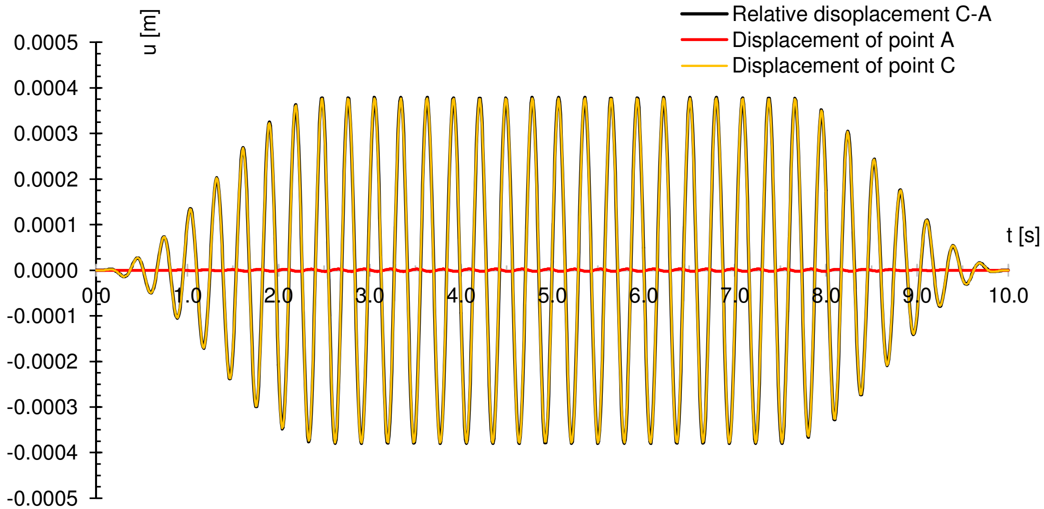

Figure 4: The displacement time history of upstream nodes A and C and relative displacements.

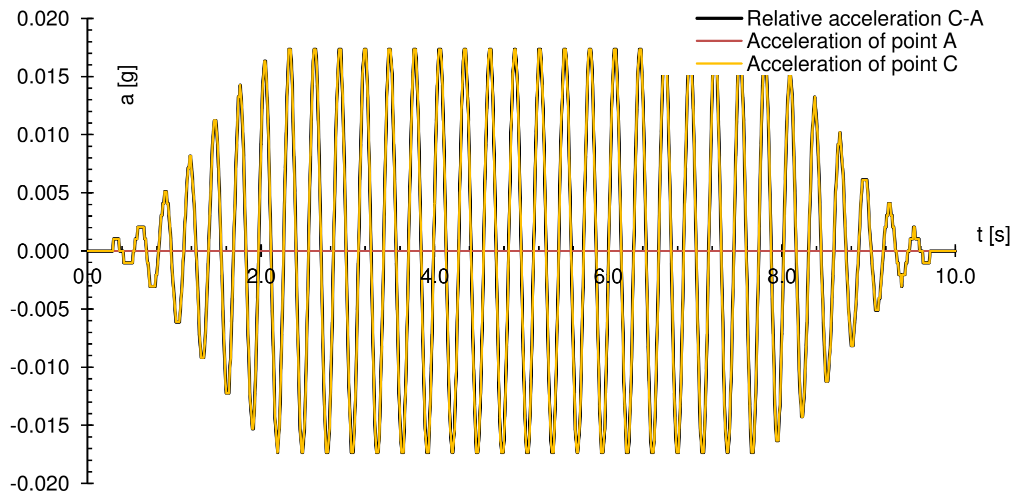

Figure 5. The acceleration time history of the upstream nodes A and relative acceleration.

CaseC – Dynamic analysis using impulsive loads

- Case C - dam and reservoir along with foundation model.
- Excitation - horizontal (Y-axis) Impulsive Stress record, applied uniformly at the base of the foundation block as specified by the formulator.
- Applied viscous boundaries - Lysmer boundaries - derived for an elastic wave propagation problem in a one-dimensional semi-infinite bar.

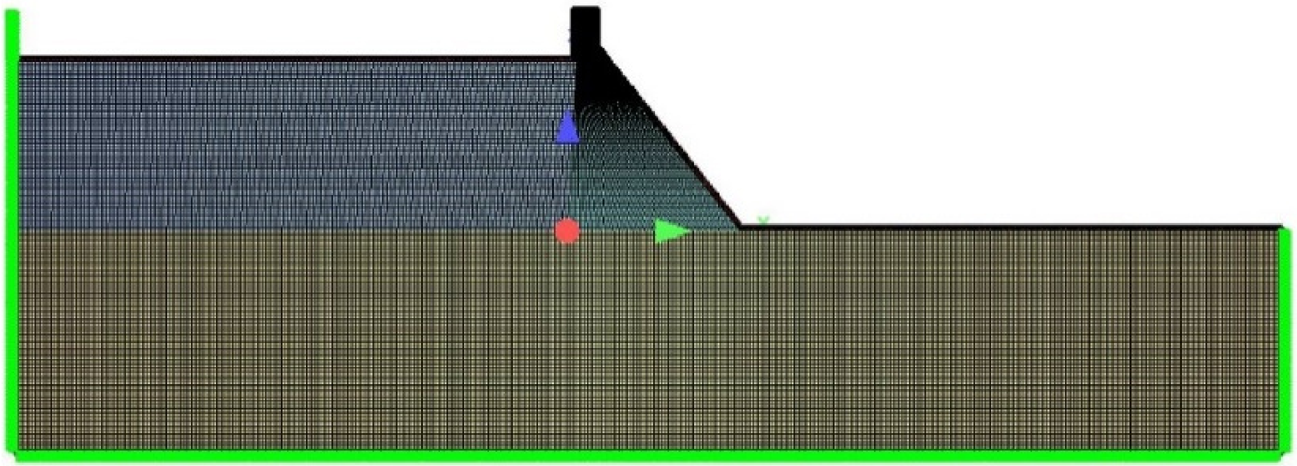

Figure 6: Fine finite element mesh (N=54440), applied for CaseC (green lines at model edges represent the dampers).

CaseC – Dynamic analysis using impulsive loads

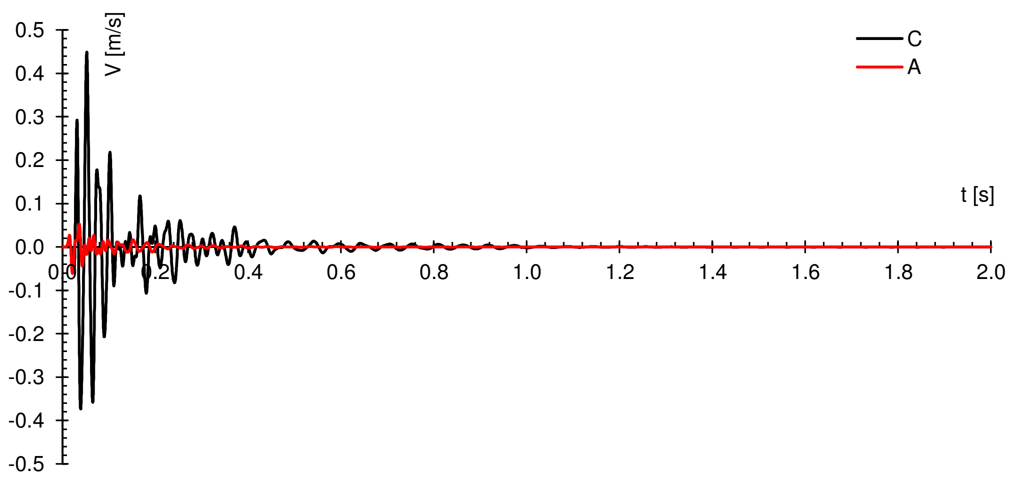

Figure 7. The acceleration time history of upstream nodes A and C for CaseC1.

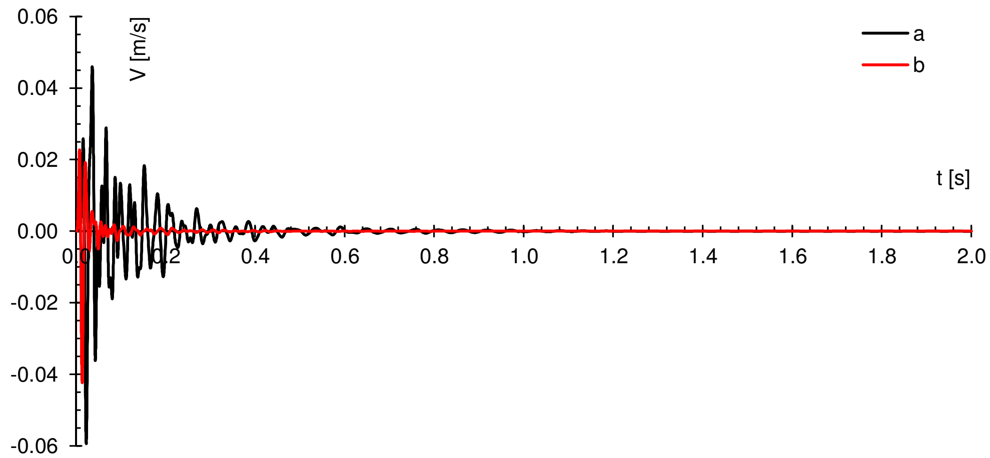

Figure 8. The acceleration time history of nodes a (middle node of dam width) and b (middle point of foundation bottom) for CaseC1.

CaseE – Non-linear dynamic analysis

- CaseE - non-linear material properties for the concrete.
- Two different dynamic loads - base of the foundation block: Taft and ETAF Record.
- Non-linear material constitutive model - Eurocode 2.
- Dam response for E1 - obtained values for acceleration and hydrodynamic pressure.
- Displacements time histories - A and C and relative displacements for CaseE2 - amplitude 0.8 m.
- Hydrodynamic pressure - dam's heel - maximal amplitude of 8000000 Pa - CaseE2

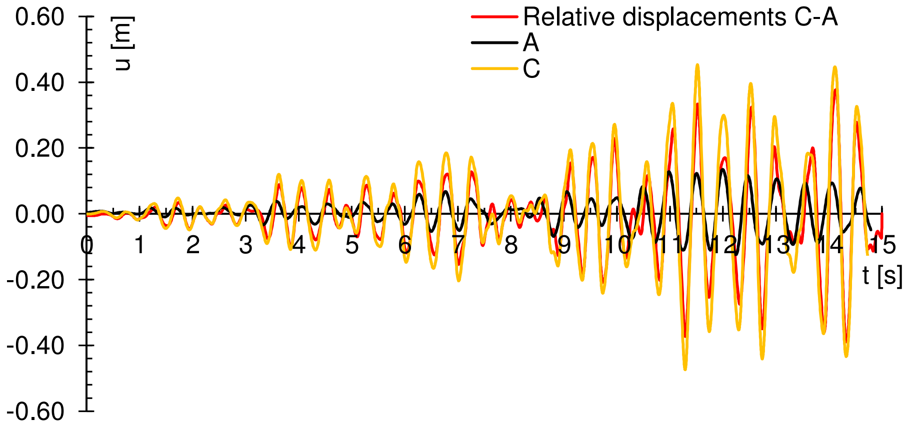

Figure 12. The acceleration time history at node A and C for CaseE2.

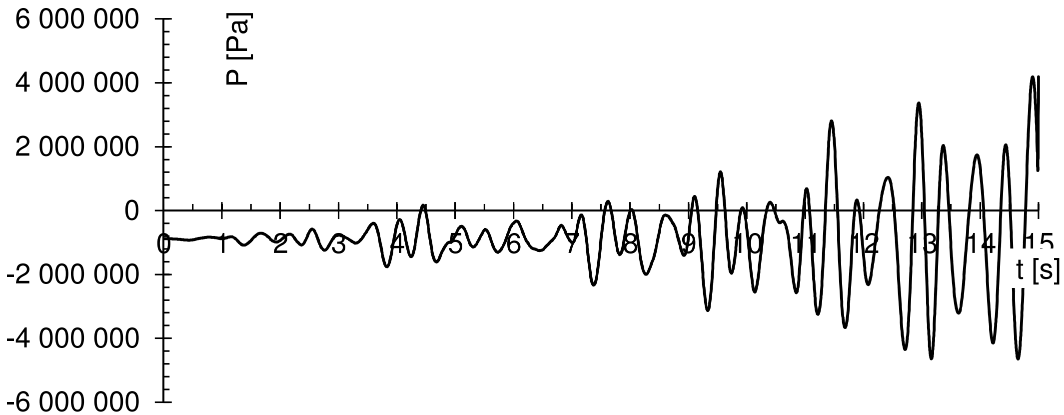

Figure 14 : The hydrodynamic pressure time history at node A for CaseE2

CaseE – Non-linear dynamic analysis

- Potential tension zone of dam - E1- display of superimposed maximal values of principal stresses II - no exceedance of tension strength - maximal value 0.89 MPa.
- Potentially damaged zone of the dam - assessed as most critical - t=14.12 s for CaseE2.

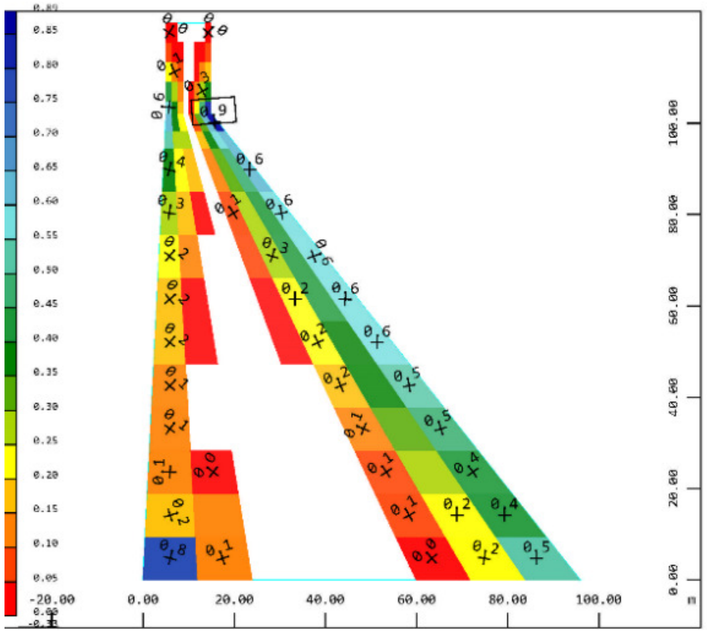

Figure 15. Display of critical case of damaged zone for CaseE1.

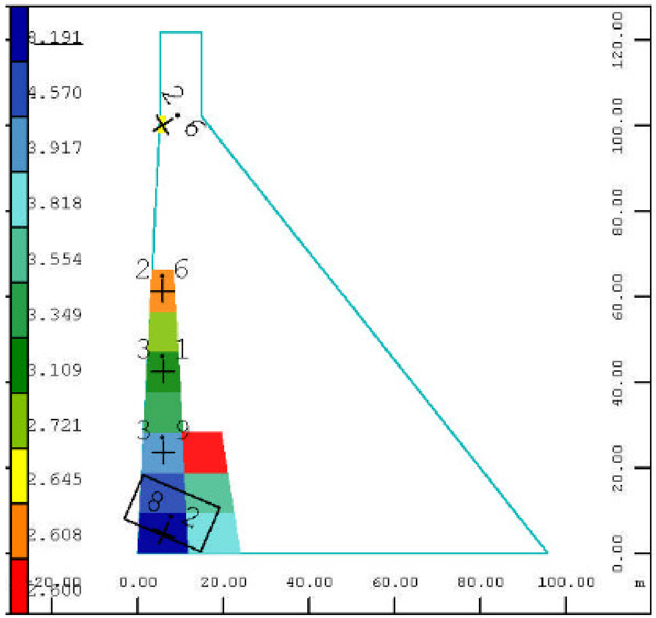

Figure 16. Display of critical case of damaged zone for CaseE2.

Conclusions

Numerical experiment of simulation of structural behaviour of Pine Flat dam - various excitation records – conclusions and findings:

- The gravity dam stability - potential damaged zones - exceeding tension stress - plastification of material.
- CaseA1 and A2 - first 6 fundamental frequencies of Pine Flat dam - water levels at 268.21 and 278.57 masl - ranging from 1.49-4.18 Hz and 1.41-4.02 Hz respectively - raised water level decreases the frequencies
- Dam response - dominant at dam crest - distribution of the relative displacements and relative accelerations during the excitation record.
- CaseC1 - analyzed values of velocities at upstream nodes A and C and nodes a (middle node of dam width) and b (middle node of foundation bottom) - modus of velocities lowering noticed - nodes more distanced then the upstream face of the dam.
- Obtained values for displacements and hydrodynamic pressure during excitation - varying approximately - 8% for water level of 268.21 to 290.0 m.
- CaseE1 - no occurrence of damaged zone
- CaseE2 - potentially damaged zone – 14.12 s - tension stress 8.20 Mpa - upstream heel of the dam.

Conclusions

From the numerical experiment of simulation of the structural behaviour of Pine Flat dam at various excitation records, following recommendations for future research can be applied:

- We are on opinion that the applied non-linear constitutive law for the concrete has large impact to the obtained results regarding the damaged zones and occurrence of plastification and cracks. We recommend specification of at least two non- linear constitute laws and execution of analysis for further research.
- Long term behaviour of dams is extensively analyzed and researched in the recent period. The concrete properties are varying in long time period. Therefore, if possible, we believe that it will be useful to determine the some of the concrete input parameters (modulus of elasticity, compressive and tension strength) of Pine Flat dam by applying non-destructive methods and based on such parameters an innovated analysis to be conducted.
- Temperature effect is important issue in case of concrete dams. So, in the future research and analysis temperature load should be considered, in order to be obtained more comprehensive insight and assessment of the dam’s behaviour.

Thank you for your attention!
Questions?