IUSS
Scuola Universitaria Superiore Pavia

ROSE School Short Course on

Seismic Behavior, Safety Evaluation and Rehabilitation of Concrete Dams

Pavia, Italy, May 13-17, 2019
Sala del Camino@ IUSS

• BACKGROUND

Hydroelectric facilities, including concrete gravity or arch dams, spillways and water intakes structures are strategic assets to our society. Large concrete dams are classified as high-risk structures where seismic failure and sudden release of reservoir will have catastrophic consequences on life safety, the economy and environment. Seismic design, safety assessment, and rehabilitation of concrete dam-foundation-reservoir system is a complex physical problem due to modelling and simulation of the related fluid-structure as well as soil-structure interactions. Concrete cracking and potential residual sliding displacements must also be taken into consideration using analyses of increasing complexity. The seismic safety assessment of concrete dams and appurtenant structures is rarely taught at the graduate level in engineering curriculum, yet each country have stringent applicable regulatory requirements. This short course is thus filling this gap in the earthquake engineering knowledge of the participants. The emphasis is put on (i) the physics, modelling and simulations of dynamic dam-foundation-reservoir interaction problems and related solution strategies, (ii) structural safety assessment procedure, and (iii) rehabilitation strategies. …

• OBJECTIVES OF THE COURSE

After following this short course the aprticipants will be able to:

- Define seismic performance criteria for concrete gravity dams, arch dams, and gated spillways,
- Specify and control the appropriate solution algorithms by a detailed understanding of the theory, assumptions and limitations inherent to dynamic modelling of fluid-structure and soil-structure interactions
- Develop analytical and numerical models of dam-foundation-reservoir system of increasing complexity including seismic coefficients, RSA, LTHA (time and frequency domain), and NLTHA,
- Identify and quantify the parameters required for the analysis (mass, stiffness, damping, and strength),
- Use structural analysis programs for seismic safety assessment of dams (CADAM-2D, EAGD84, …),
- Incorporate analysis results into an informed decision making process related to the adequacy of seismic performance and possible remedial actions.

• ABOUT THE INSTRUCTORS:

Pierre Léger is Professor of structural engineering at École Polytechnique de Montréal affiliated to Montreal University, Canada. He graduated from Ottawa University in 1977 (BScA) and Laval University (MSc) in 1979. He then worked as a structural engineer for Tecsult Inc. until 1982. He obtained a Ph.D in Structural Engineering from the University of California, Berkeley, in 1986. He taught structural engineering from 1986 to 1992 at McGill University before joining École Polytechnique where he was the co-holder for 10 years of a research chair related to structural safety of concrete dams. His research work is currently focusing on numerical analysis and experimental study of the structural behaviour and safety of concrete dams and hydraulic structures, inelastic dynamic analysis and earthquake resistant design of buildings. He has acted as a consultant on several projects related structural analysis and seismic safety assessment of nuclear power plants, and concrete dams, including the Daniel Johnson Multiple Arch Dam that is the highest structure of this kind in the world at 214m. P. Léger has authored more than 100 journal papers and book chapters and 125 conference proceedings related to his research activities.

Palazzo del Broletto
Piazza della Vittoria n. 15
27100 Pavia - Italia
Tel. 39 0382 375811 Fax +39 0382 375899

info@iusspavia.it
www.iusspavia.it
C.F. 96049740184
P. IVA 02202080186

COURSE SCHEDULE May 13-17, 2019 (5hrs /day x 5 days = 25 hrs)

Day 1, May 13

Morning Session: 09:00-12:00

1. INTRODUCTION - (Motivation, Scope and Objectives)

- Types of concrete dams and appurtenant structures
- Historical seismic performance of dam-foundation-resevoir and failure mechanisms
- Limitations of past seismic design procedures and need for FE models and simulations
- Overview of the dynamic dam-reservoir-foundation interaction problem
- FE commercial and research software (SAP2000, ABAQUS, LS-Dyna, DIANA, CADAM, EAGD84, EACD3D, RS-DAM, OpenSees)
- Objectives, scope and format of the short course, documentation, software

2. STRUCTURAL DYNAMICS FOR DAM-FOUNDATION-RESERVOIR ANALYSIS

- Equations of dynamic equilibrium (SDOF, MDOF)
- Response spectrum analysis - (mode shapes, effective modal mass, static correction for higher modes, modal combination rules and principal stresses)
- Time domain solution strategy (Implicit vs explicit solvers, NB, HHT integrators, linear and nonlinear simulations (cracking, sliding).

Afternoon Session: 14:00-16:00

(STRUCTURAL DYNAMICS FOR DAM-FOUNDATION-RESERVOIR ANALYSIS)

- Frequency domain solution strategy (FFT, impedance, compliance, transfer functions)
- Wave propagation in continuous media (elastic half-space, wave reflexion, refraction, absorption and boundary conditions for infinite media)
- *Practical applications - LAS (time domain vs frequency domain) - SAP2000 (RSA)*

Day 2, May 14

Morning Session: 09:00-12:00

3. SEISMIC ASSESSMENT AND PERFORMANCE CRITERIA

- Dam safety guidelines (ICOLD, FEMA, FERC, USACE, USBR, CFBR)
- Seismic hazard, return periods, target spectrum (OBE, SEE, MCE ,response spectra, UHS, CMS)
- Selection and scaling of ground motions
- Reservoir induced seismicity

4. MATERIAL PROPERTIES FOR STATIC AND SEISMIC ANALYSIS

- Mass, Stiffness, Damping properties; source of data
- Selection of material properties; State-of-practice and dam safety guidelines
- Mass concrete stress-strain response, tensile strength, effect of strain rate, damping
- Shear strength of rock-rock, rock-concrete, concrete-concrete joints
- Compatibility between static and dynamic analyses
- Concrete strength and multi-axial stress state
- Smeared crack, discrete crack, contact element models

Afternoon Session: 14:00-16:00

5. FLUID STRUCTURE INTERACTION

- Static, hydrostatic, uplift pressures, dynamic interactions,
- Added mass concept (basic assumptions)
- Mathematical formulation of dam-reservoir interaction problem
- Westergaard added mass, Effects of water compressibility, Finite length of reservoir,
- Extension of Westergaard added mass for inclined and curved upstream faces

Day 3, May 15

Morning Session: 09:00-12:00

(FLUID STRUCTURE INTERACTION)

- FE analysis using liquid elements - Frequency domain vs Time domain
- Cavitation, Transient uplift pressures in cracks, Effects of sediments
- Uplift pressures for post-earthquake stability assessment
- *Case Study - Practical applications : CADAM2D, SAP2000, EAGD84*

6. DAM- FOUNDATION INTERACTION

- Static, dynamic interactions (kinetic, inertial),
- Wave propagation in foundation, material, radiation damping
- Mathematical formulation of dam-foundation interaction problem
- Massless foundation model (use and limitations)

Afternoon Session: **14:00-16:00**

(DAM- FOUNDATION INTERACTION)

- Mass foundation model - Frequency domain solution (boundary conditions)
- Deconvolution of ground motion accelerograms (SHAKE, DEEPSOIL computer programs)
- Mass foundation model - Time domain solution (boundary conditions, deconvolved input model)
- *Case- study Practical applications :CADAM2D, SHAKE, SAP2000*

Day 4, May 16

Morning Session: **09:00-12:00**

7. DEVELOPMENT, VERIFICATION AND VALIDATION OF DAM-FOUNDATION-RESERVOIR MODELS

- Three pillars of sciences and engineering: (i) theory, (ii) experimental observations, (iii) computational model and simulations
- Source of errors in computational modelling and simulations
- Model and simulations verification and validation strategies (V&V)
- Propagation and quantification of uncertainties
- ICOLD-USSD Numerical benchmarks

8. GRAVITY DAMS

- Loads and load combinations, Performance criteria
- Computer programs - CADAM2D, EAGD84, SAP2000...
- Static analysis - initial condition for seismic analysis
- Dynamic characteristic, period of vibration, mode shapes, effective modal mass
- Seismic coefficient, Pseudo-dynamic method (response spectrum analysis)

Afternoon Session: 14:00-16:00

(GRAVITY DAMS)

- Frequency domain analysis (EAGD84), - Linear Time domain analysis
- *Case - Study Practical applications CADAM2D, EAGD-84, SAP2000*

Day 5, May 17

Morning Session: 09:00-12:00

(GRAVITY DAMS)

- Rigid body dynamic (rocking - sliding) and assessment of residual displacements
- Nonlinear Time domain analysis
- Seismic safety assessment and rehabilitation
- *Case - Study Practical applications SAP2000, RS-DAM*

9. ARCH DAMS

- Loads and load combinations, Performance criteria
- Computer Programs - SAP2000, EACD3D, ABAQUS, ...
- Static analysis - phases of construction - initial condition for seismic analysis
- Dynamic characteristic, period of vibration, mode shapes, effective modal mass
- RSA, Frequency domain analysis, Time domain analysis
- Effect of spatial variation of ground motions
- Seismic safety assessment and rehabilitation
- *Case - Study*

Afternoon Session: 14:00-16:00

10. GATED SPILLWAYS AND WATER INTAKE STRUCTURES

- Spillway characterisrics, gate operation
- Loads and load combinations, Performance criteria, allowable displacement
- Dynamic characteristic, period of vibration, mode shapes, effective modal mass
- Hydrodynamic fluid-gate interactions,
- Floor (in-structure) response spectrum, seismic response of gate lifting equipment
- Water intake structures
- Seismic safety assessment and rehabilitation
- *Case - Study*

Seismic Behavior, Safety Evaluation and Rehabilitation of Concrete Dams

1. INTRODUCTION - (Motivation, Scope and Objectives)

- Types of concrete dams and appurtenant structures
- Historical seismic performance of dam-foundation-resevoir and failure mechanisms
- Limitations of past seismic design procedures and need for FE models and simulations
- Overview of the dynamic dam-reservoir-foundation interaction problem
- FE commercial and research software (SAP2000, ABAQUS, LS-Dyna, DIANA, CADAM, EAGD84, EACD3D, RS-DAM, OpenSees)
- Objectives, scope and format of the short course, documentation, software

2. STRUCTURAL DYNAMICS FOR DAM-FOUNDATION-RESERVOIR ANALYSIS

- Equations of dynamic equilibrium (SDOF, MDOF)
- Response spectrum analysis - (mode shapes, effective modal mass, static correction for higher modes, modal combination rules and principal stresses)
- Time domain solution strategy (Implicit vs explicit solvers, NB, HHT integrators, linear and nonlinear simulations (cracking, sliding).
- Frequency domain solution strategy (FFT, impedance, compliance, transfer functions)
- Wave propagation in continuous media (elastic half-space, wave reflexion, refraction, absorption and boundary conditions for infinite media).
- *Practical applications - LAS (time domain vs frequency domain) - SAP2000 (RSA)*

3. SEISMIC ASSESSMENT AND PERFORMANCE CRITERIA

- Dam safety guidelines (ICOLD, FEMA, FERC, USACE, USBR, CFBR)
- Seismic hazard, return periods, target spectrum (OBE, SEE, MCE ,response spectra, UHS, CMS)
- Selection and scaling of ground motions
- Reservoir induced seismicity

4. MATERIAL PROPERTIES FOR STATIC AND SEISMIC ANALYSIS

- Mass, Stiffness, Damping properties; source of data
- Selection of material properties; State-of-practice and dam safety guidelines
- Mass concrete stress-strain response, tensile strength, effect of strain rate, damping
- Shear strength of rock-rock, rock-concrete, concrete-concrete joints
- Compatibility between static and dynamic analyses
- Concrete strength and multi-axial stress state
- Smeared crack, discrete crack, contact element models

5. FLUID STRUCTURE INTERACTION

- Static, hydrostatic, uplift pressures, dynamic interactions,
- Added mass concept (basic assumptions)
- Mathematical formulation of dam-reservoir interaction problem
- Westergaard added mass, Effects of water compressibility, Finite length of reservoir,
- Extension of Westergaard added mass for inclined and curved upstream faces
- FE analysis using liquid elements - Frequency domain vs Time domain
- Cavitation, Transient uplift pressures in cracks, Effects of sediments
- Uplift pressures for post-earthquake assessment
- *Case Study - Practical applications : CADAM2D, SAP2000, EAGD84*

6. DAM- FOUNDATION INTERACTION

- Static, dynamic interactions (kinetic, inertial),
- Wave propagation in foundation, material, radiation damping
- Mathematical formulation of dam-foundation interaction problem
- Massless foundation model (use and limitations)
- Mass foundation model - Frequency domain solution (boundary conditions)
- Deconvolution of ground motion accelerograms (SHAKE, DEEPSOIL computer programs)
- Mass foundation model - Time domain solution (boundary conditions, deconvolved input model)
- *Case- study Practical applications :CADAM2D, SHAKE, SAP2000*

7. DEVELOPMENT, VERIFICATION AND VALIDATION OF DAM-FOUNDATION-RESERVOIR MODELS

- Three pillars of sciences and engineering: (i) theory, (ii) experimental observations, (iii) computational model and simulations
- Source of errors in computational modelling and simulations
- Model and simulations verification and validation strategies (V&V)
- Propagation and quantification of uncertainties
- ICOLD-USSD Numerical benchmarks

8. GRAVITY DAMS

- Loads and load combinations, Performance criteria
- Computer programs - CADAM2D, EAGD84, SAP2000..
- Static analysis - initial condition for seismic analysis
- Dynamic characteristic, period of vibration, mode shapes, effective modal mass
- Seismic coefficient, Pseudo-dynamic method (response spectrum analysis)
- Frequency domain analysis (EAGD84), - Linear Time domain analysis
- *Case - Study Practical applications CADAM2D, EAGD-84, SAP2000*
- Rigid body dynamic (rocking - sliding) and assessment of residual displacements
- Nonlinear Time domain analysis
- Seismic safety assessment and rehabilitation
- *Case - Study Practical applications, SAP2000, RS-DAM*

9. ARCH DAMS

- Loads and load combinations, Performance criteria
- Computer Programs - SAP2000, EACD3D, ABAQUS, …
- Static analysis - phases of construction - initial condition for seismic analysis
- Dynamic characteristic, period of vibration, mode shapes, effective modal mass
- RSA, Frequency domain analysis, Time domain analysis
- Effect of spatial variation of ground motions
- Seismic safety assessment and rehabilitation
- *Case - Study*

10. GATED SPILLWAYS AND WATER INTAKE STRUCTURES

- Spillway characterisrics, gate operation
- Loads and load combinations, Performance criteria, allowable displacement
- Dynamic characteristic, period of vibration, mode shapes, effective modal mass
- Hydrodynamic fluid-gate interactions,
- Floor (in-structure) response spectrum, seismic response of gate lifting equipment
- Water intake structures
- Seismic safety assessment and rehabilitation
- *Case - Study*