

Lecture Notes in Civil Engineering

Gabriella Bolzon  
Donatella Sterpi  
Guido Mazzà  
Antonella Frigerio *Editors*

# Numerical Analysis of Dams

Proceedings of the 15th ICOLD  
International Benchmark Workshop

 Springer

# **Lecture Notes in Civil Engineering**

Volume 91

## **Series Editors**

Marco di Prisco, Politecnico di Milano, Milano, Italy

Sheng-Hong Chen, School of Water Resources and Hydropower Engineering,  
Wuhan University, Wuhan, China

Ioannis Vayas, Institute of Steel Structures, National Technical University of  
Athens, Athens, Greece

Sanjay Kumar Shukla, School of Engineering, Edith Cowan University, Joondalup,  
WA, Australia

Anuj Sharma, Iowa State University, Ames, IA, USA

Nagesh Kumar, Department of Civil Engineering, Indian Institute of Science  
Bangalore, Bengaluru, Karnataka, India

Chien Ming Wang, School of Civil Engineering, The University of Queensland,  
Brisbane, QLD, Australia

**Lecture Notes in Civil Engineering (LNCE)** publishes the latest developments in Civil Engineering—quickly, informally and in top quality. Though original research reported in proceedings and post-proceedings represents the core of LNCE, edited volumes of exceptionally high quality and interest may also be considered for publication. Volumes published in LNCE embrace all aspects and subfields of, as well as new challenges in, Civil Engineering. Topics in the series include:

- Construction and Structural Mechanics
- Building Materials
- Concrete, Steel and Timber Structures
- Geotechnical Engineering
- Earthquake Engineering
- Coastal Engineering
- Ocean and Offshore Engineering; Ships and Floating Structures
- Hydraulics, Hydrology and Water Resources Engineering
- Environmental Engineering and Sustainability
- Structural Health and Monitoring
- Surveying and Geographical Information Systems
- Indoor Environments
- Transportation and Traffic
- Risk Analysis
- Safety and Security

To submit a proposal or request further information, please contact the appropriate Springer Editor:

- Mr. Pierpaolo Riva at [pierpaolo.riva@springer.com](mailto:pierpaolo.riva@springer.com) (Europe and Americas);
- Ms. Swati Meherishi at [swati.meherishi@springer.com](mailto:swati.meherishi@springer.com) (Asia—except China, and Australia, New Zealand);
- Dr. Mengchu Huang at [mengchu.huang@springer.com](mailto:mengchu.huang@springer.com) (China).

**All books in the series now indexed by Scopus and EI Compendex database!**

More information about this series at <http://www.springer.com/series/15087>

Gabriella Bolzon · Donatella Sterpi ·  
Guido Mazzà · Antonella Frigerio  
Editors

# Numerical Analysis of Dams

Proceedings of the 15th ICOLD International  
Benchmark Workshop

*Editors*

Gabriella Bolzon  
Department of Civil and Environmental  
Engineering (DICA)  
Politecnico di Milano  
Milano, Italy

Donatella Sterpi  
Department of Civil and Environmental  
Engineering (DICA)  
Politecnico di Milano  
Milano, Italy

Guido Mazzà  
Italian Committee on Large Dams  
(ITCOLD)  
Roma, Italy

Antonella Frigerio  
Ricerca sul Sistema Energetico—RSE SpA  
Milano, Italy

ISSN 2366-2557                      ISSN 2366-2565 (electronic)  
Lecture Notes in Civil Engineering  
ISBN 978-3-030-51084-8              ISBN 978-3-030-51085-5 (eBook)  
<https://doi.org/10.1007/978-3-030-51085-5>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2021

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# ICOLD Technical Committee

## Computational Aspects of Analysis and Design of Dams

ICOLD, the International Commission on Large Dams, appointed in 1988 the ad hoc Committee Computational Aspects of Analysis and Design of Dams that was converted into a permanent Technical Committee in 2005. The main objective assigned to the Committee was to fill the gap existing between the specialists of numerical modelling and the different professional figures involved in the dam sector, i.e. dam designers, authorities, and managers. A second objective was to contribute to the diffusion of engineering software in the field of dam engineering, introducing new approaches in a context traditionally refractory to innovations. The Committee is also strongly committed in the transfer of experience, skill and knowledge across generations.

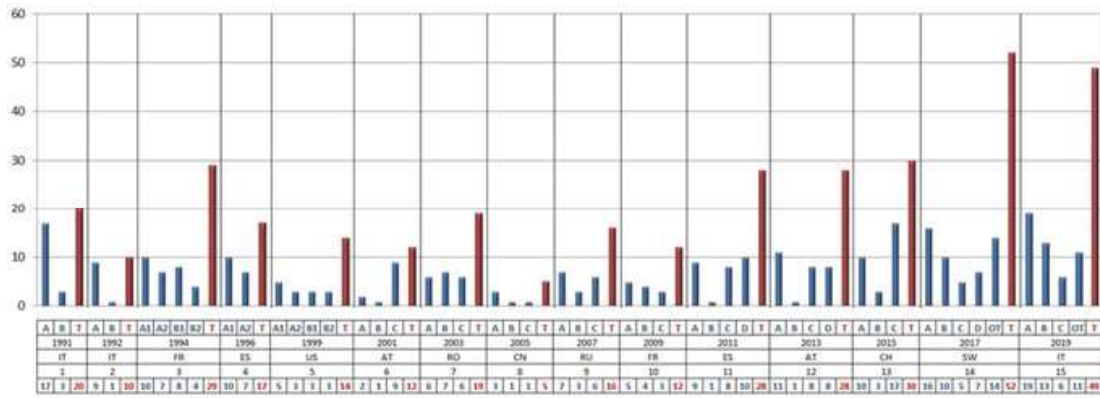
The work done by the Committee during its long activity lead to the issuing of three Technical Bulletins (1–3).

Present and future activities of the Committee are oriented towards:

- creating a stronger link between the observed dam behaviour and the modelling process, with the aim to contribute to the preservation and maintenance of existing dams;
- making advanced tools increasingly available to the professional world, for improved design of new dams;
- promoting mathematical modelling improvements to approach safety-related problems that cannot at present be properly analysed.
- issuing guidelines to be used for educational purposes in the current practice.

The benchmarking program started in Bergamo (Italy) in 1991 and has continued over the time in different Countries, with the 15th event of the series organized in Milano (Italy) on 9–11 September 2019.

The active involvement in the benchmarking activities of technicians operating in the dam sector is visualized in Fig. 1. The examination of these data suggests the following considerations.



**Fig. 1** Contributors to the 15 Benchmark Workshops held from 1991 to 2019 per theme and date (49 themes proposed in total); red figures and bars indicate the total number of contributors

- Until the 10th Benchmark Workshop (year 2009), the number of active participants (who provided a solution of the proposed problems) was mainly between 10 and 20; this number has been rapidly increasing in the subsequent editions.
- The total number of attendees has been always quite high, in the order of 100 people, with peaks of up to 190 participants in the last event in Milan.
- From a geographical point of view, the Benchmark Workshops took place mainly in European locations, with the exceptions of Denver (USA) in 1999 and Wuhan (China) in 2005. European centrality is partly linked to the prevalence of European members in the ICOLD Committee “Computational Aspects of Analysis and Design of Dams”. However, the interest in the numerical modelling of dams has been increasing in the last few years in US and China, and these countries are prone to host these events soon.

The problem description together with the input data, and a report written by the formulator (about the individual results and their comparison) are collected by the proceedings that are available in ICOLD website.

A capitalization activity of the tremendous amount of data at disposal has been recently started with the aim to facilitate the accessibility and the critical review of the content of the Benchmark Workshops held so far. A new Bulletin—or an equivalent document—will provide a synthesis of the results, outlining the progresses made by numerical methods in dam engineering.

The benchmarking activities represent a reference for the whole dam community, and in particular for young engineers, engaged in the challenging task of ensuring dam safety.

# Preface

This book collects the contributions presented at the 15th International Benchmark Workshop on Numerical Analysis of Dams held in Milano in September 2019.

These Benchmark Workshops are promoted by the Technical Committee on ‘Computational Aspects of Analysis and Design of Dams’ of ICOLD (International Commission of Large Dams) to provide an opportunity for engineers, researchers and operators to present and exchange their experiences and the latest developments related to the design, performance and monitoring of dams.

This series of almost biannual events was launched in Italy in 1991 and then hosted in several Countries all over the World. The topics and the approaches considered in the different editions reflect the evolution of the computer analysis tools and of the safety assessment criteria over the last decades.

The first benchmarks were focused on the validation of dedicated numerical codes, in their initial development phase. The predictive capabilities of available sophisticated computing facilities represent the challenges of the recent work. The main issues concern the selection of the most appropriate geometrical and constitutive models and the calibration of the parameters that define the conditions to be analyzed in reality.

The 15th International Benchmark Workshop on Numerical Analysis of Dams dealt with three main topics.

Theme A considers the earthquake response of a concrete gravity dam. The role of the foundation size and mass in the model, the interaction with the dam body and the non-linear material response represent the main debated aspects, with the ultimate goals of identifying the key uncertainties causing differences in results and developing the best practices in the advanced dynamic analysis of these massive structures. The benchmark problem has been formulated by: Jerzy W. Salamon and Christopher Wood (U.S. Bureau of Reclamation, USA); M. Amin Hariri-Ardebili (University of Colorado at Boulder, USA); Richard Malm (KTH Royal Institute of Technology, Sweden) and Giorgia Faggiani (Ricerca sul Sistema Energetico—RSE S.p.A., Italy).



Theme B refers to the seismic analysis of embankment dams. A case study is defined with the aim of understanding how different assumptions on the constitutive model of the rockfill material may affect the results. The stability conditions (in proximity to failure) of the dam after the assigned earthquake and, additionally, the potential damages of the bituminous facing represent problems to be specifically addressed in the proposal formulated by: Giacomo Russo (University of Napoli Federico II and University of Cassino and Southern Lazio, Italy); Manuela Cecconi, Alessia Vecchietti and Vincenzo Pane (University of Perugia, Italy); Andrea Fiorino and Sergio De Marco (So.Ri.Cal, Italy).

Theme C introduces to the pre-failure and failure behavior of a dyke on soft subsoil. The results of coupled hydro-mechanical analyses are compared with the monitoring data collected in a full-scale controlled failure test. The potential of current plane analyses to predict the failure and pre-failure response of the dyke is assessed. The improvement possibly provided by three-dimensional models taking into account the spatial variability of the soil layers is further evaluated. The benchmark formulation and the experimental information have been provided by: Cristina Jommi (Politecnico di Milano, Italy, and Delft University of Technology, the Netherlands); Tom de Gast, Elisa Ponzoni, Niccolò Valimberti and Stefano Muraro (Delft University of Technology, the Netherlands); Ludolph Wentholt and Henk van Hemert (STOWA, the Netherlands).

This volume contains both the problem definition (data concerning geometry, material properties, loading conditions, seismic input, etc.) and the throughout synthesis of the results, worked out by the formulators of each theme, together with the individual contributions by the benchmark participants.

Furthermore, the book introduces a series of topics relevant to the present practice in the computational analysis of dams and of the relevant appurtenant structures. The contributions collected in this volume focus on the study of dams with interesting features (Eberlaste, Grand Dixence, Nam Ngum 3, Ridracoli). Specific aspects of the numerical analysis of these infrastructures are discussed, with an open eye on: monitoring and identification problems; uncertainty quantification and reduction; classification models; visualisation tools and machine learning; cost risk assessment. These topics are proposed in the frame of an Open Theme session that allows to identify possible topics to be proposed in the future Benchmark Workshops.

All together, these contributions constitute a valuable reference for the whole engineering community concerned with safety, planning, design, construction, operation and maintenance of dams.

The 15th International Benchmark Workshop was organized in the main Italian financial city that hosts the headquarters of several global Companies and the seat of many International Institutions. Milano represents the cultural site and an attraction place for many professionals, including designers, fashion-operators, artists, photographers. The rich environment created by its historical heritage, together with several new quarters designed by outstanding architecture studios make Milano the Italian city of glamour with a vivid cultural and social life.

The editors acknowledge the contribution given by several Colleagues for the successful realization of the event and wish to express their deep gratitude to them. The Editors do also gratefully thank:

- the Team of Formulators for the tremendous work done to define the theme content and for providing the synthesis of the results obtained by the several participants, and Giorgia Faggiani for her assistance in the editing process;
- ITCOLD, Politecnico di Milano with the Department of Civil and Environmental Engineering, the research institute Ricerca sul Sistema Energetico-RSE, the Consiglio Nazionale degli Ingegneri for the organizational support;
- the sponsors who provided financial support and facilities for the workshop and the technical visits;
- Regione Lombardia and Comune di Milano for the patronage offered at the event.



Promoted by the ICOLD Technical Committee Computational Aspects of Analysis and Design of Dams, and organized by Politecnico di Milano, ITCOLD, Consiglio Nazionale degli Ingegneri, Ricerca sul Sistema Energetico-RSE.



ICOLD Technical Committee A  
Computational Aspects of Analysis and Design of Dams



Under the patronage of Comune di Milano and Regione Lombardia.



With the sponsorship of ENEL, Mapei, Gruppo CVA, Romagna Acque, EDISON, A2A, Gelmi, and the hospitality of ENEL and Consorzio di Bonifica di Piacenza for the technical visits to Isola Serafini weir and Molato Dam.



Milano, Italy  
Milano, Italy  
Roma, Italy  
Milano, Italy

Gabriella Bolzon  
Donatella Sterpi  
Guido Mazzà  
Antonella Frigerio

# Contents

## **Theme A: Seismic Analysis of Pine Flat Concrete Dam**

<b>Seismic Analysis of Pine Flat Concrete Dam: Formulation and Synthesis of Results</b> . . . . .	3
J. W. Salamon, C. Wood, M. A. Hariri-Ardebili, R. Malm, and G. Faggiani	
<b>Non-linear Behavior of a Concrete Gravity Dam During Seismic Excitation: A Case Study of the Pine Flat Dam</b> . . . . .	99
J. Enzell, R. Malm, R. Abbasiverki, and L. Ahmed	
<b>Assessment of the Dynamic Response of Pine Flat Concrete Gravity Dam. FEM Simulation of Dam-Foundation Interaction</b> . . . . .	113
G. Faggiani, P. Masarati, and A. Frigerio	
<b>Seismic Analysis and Damage Evaluation of Pine Flat Concrete Dam</b> . . . . .	129
M. Farrokh	
<b>Numerical Seismic Analysis of Pine Flat Dam Using Finite Difference Method</b> . . . . .	145
J.-R. Lherbier and F. Andrian	
<b>Dynamic Analysis of Pine Flat Concrete Dam: Acoustic Fluid-Structural Interaction with ANSYS Workbench</b> . . . . .	161
T. Menouillard, A. D. Tzenkov, and M. V. Schwager	
<b>Seismic Analysis of Pine Flat Concrete Dam</b> . . . . .	175
S. Mitovski, L. Petkovski, G. Kokalanov, V. Kokalanov, and F. Panovska	
<b>Seismic Analysis of Pine Flat Concrete Dam: Comparison of Numerical Results from 2D and 3D Analysis</b> . . . . .	191
N. Monteiro Azevedo, M. L. Braga Farinha, R. Câmara, and N. Schclar Leitão	

<b>Seismic Analysis of Pine Flat Concrete Dam</b> .....	205
N. Naji-Mahalleh	
<b>Seismic Excitation of a Concrete Dam: Analysis of the Influence of Modelling Approaches and Concrete Material Non-linearity</b> .....	223
E. Panteki and M. Goldgruber	
<b>Modal, Dynamic and Seismic Analyses of the Pine Flat Concrete Gravity Dam</b> .....	237
P. Peton and T. Thénint	
<b>Seismic Analyses of Pine Flat Dam: Simplified Use of Viscous Spring Boundaries and Anisotropic Damage in the Principal Directions with the Ability of Cracks Re-Closure</b> .....	253
E. Robbe, E. Grimal, and G. Devesa	
<b>Evaluation of Seismic Wave Propagation in the Analysis of Concrete Dams: Pine Flat Dam Benchmark Study</b> .....	263
J. W. Salamon, C. Wood, J. Manie, and A. Geister	
<b>Finite Element Analyses of a Concrete Gravity Dam: Investigation on Static and Dynamic Behavior</b> .....	277
M. Scolari, A. Bado, D. Gualco, L. Buraschi, and R. Valsecchi	
<b>Analysis of Pine Flat Dam Considering Fluid-Soil-Structure Interaction and a Linear-Equivalent Model</b> .....	295
A. F. Stabile, P. Labbé, and A. Nguyen	
<b>2D Seismic Analysis of Pine Flat Concrete Gravity Dam Including Mass of Foundation: Approach with Infinite Elements</b> .....	309
E. J. Staudacher and G. Zenz	
<b>Seismic Analysis of Pine Flat Concrete Dam</b> .....	323
W. Su, J.-T. Wang, and Y.-J. Xu	
<b>Seismic Analysis of Pine Flat Concrete Dam</b> .....	339
S. Valente, Q. He, and C. Capriulo	
<b>Seismic Behavior of Pine Flat Concrete Gravity Dam Using Microplane Damage-Plasticity Model</b> .....	353
S. Vorlet, P. Manso, and G. De Cesare	
<b>Earthquake Soil Structure Interaction Analysis of a Gravity Dam</b> .....	369
H. Yang, H. Wang, J. W. Salamon, and B. Jeremic	
<b>Dynamic Foundation-Fluid-Structure Interaction of a Concrete Gravity Dam: Influence of Input Signal Frequency Content and of Water Modelling on Wave Propagations—Example of Pine Flat Dam</b> .....	381
V. Mouy and X. Molin	

## **Theme B: Seismic Analysis of Menta Embankment Dam**

<b>Seismic Analyses of Menta Embankment Dam: Formulation and Synthesis of Results</b> . . . . .	399
G. Russo, M. Cecconi, A. Vecchiotti, V. Pane, A. Fiorino, and S. De Marco	
<b>Numerical Analysis of the Seismic Behavior of the Menta BFR Dam</b> . . . . .	419
D. Aliberti, M. Vecchiotti, E. Cascone, and G. Biondi	
<b>Seismic Analysis of Menta Embankment Dam</b> . . . . .	439
E. Catalano, R. Stucchi, M. Agosti, and R. Crapp	
<b>Numerical Simulation of Seismic Behavior of Menta Dam, Italy</b> . . . . .	453
A. K. Chugh	
<b>Static and Dynamic Analysis of a Bituminous Faced Rockfill Dam</b> . . . . .	471
A. Freuis, A. Kainrath, S. Krstić, and M. Smesnik	
<b>Numerical Investigation on the Seismic Responses of the Menta Embankment Dam</b> . . . . .	485
Z. Z. Fu, Z. K. Mi, and K. M. Wei	
<b>Seismic Analyses of Menta Embankment Dam</b> . . . . .	501
V. B. Glagovsky and E. D. Gibyanskaya	
<b>Elasto-Plastic Finite Element Analysis of Menta Dam Under Two Earthquake Excitations</b> . . . . .	513
J. Liu, D. Zou, H. Liu, and F. Wang	
<b>Seismic Analyses for Menta Embankment Dam: Nonlinear Dynamic Analyses with HS-Small (Hardening Small Strain) Model</b> . . . . .	527
H. Lu and C. Athanasiu	
<b>Numerical Analysis of the Menta Dam</b> . . . . .	541
T. Mészáros, M. Bakeš, and M. Minárik	
<b>Modeling the Seismic Behavior of Bituminous Faced Rockfill Dam with Hujeux Model Implemented in Code_Aster</b> . . . . .	561
A. Mondoloni, P. Kolmayer, and V. Alves Fernandes	
<b>Seismic Behavior of a Bituminous-Faced Rock-Fill Dam: The Menta Dam</b> . . . . .	579
L. Petkovski, S. Mitovski, and F. Panovska	
<b>Seismic Analyses of Menta Embankment Dam: An Elasto-Plastic Model with a Stress-Strain Dependent Stiffness and a Composite Yielding Surface</b> . . . . .	605
F. Raggi	

<b>Nonlinear FEM Analysis of the Seismic Behavior of the Menta Bituminous-Face Rockfill Dam</b> . . . . .	619
A. D. Tzenkov and M. V. Schwager	
<b>Theme C: Coupled Hydro-Mechanical Analysis of the Pre-failure and the Failure Behaviour of a Dyke on Soft Subsoil</b>	
<b>Coupled Hydro-Mechanical Analysis of the Pre-failure and the Failure Behaviour of a Dyke on Soft Subsoil: Formulation and Synthesis of Results</b> . . . . .	645
C. Jommi, D. Sterpi, T. de Gast, S. Muraro, E. Ponzoni, and H. van Hemert	
<b>SPH Modelling of the Kagerplassen Dyke Failure</b> . . . . .	667
A. Amicarelli and E. Abbate	
<b>Analysis of the Pre-failure and Failure Behavior of a Levee on Soft Subsoil</b> . . . . .	681
M. Bakeš, T. Mészáros, and M. Minárik	
<b>Coupled Hydro-Mechanical Analysis of the Leendert de Boerpolder Dyke Stress-Test</b> . . . . .	693
C. Marulanda, J. Tello, and D. León-Vanegas	
<b>Analysis of Pre-failure and Failure of a Levee on Soft Soil with Modified Cam-Clay Model in DIANA</b> . . . . .	711
M. V. Schwager, A. D. Tzenkov, and G. M. A. Schreppers	
<b>Open Themes</b>	
<b>Numerical Analysis of the 210 m-High Nam Ngum 3 CFRD</b> . . . . .	749
F. Andrian, N. Ulrich, and M. Monkachi	
<b>Elasto-Plastic Damage Time-History Analysis of Dams: The Case of Ridracoli</b> . . . . .	763
G. Buffi, P. Manciola, L. De Lorenzis, V. Gusella, M. Mezzi, C. Tamagnini, A. Gambi, and G. Montanari	
<b>Heightening of Very High Gravity Dams: The Case Study of the Grande Dixence</b> . . . . .	775
B. Clerc, P. Manso, and G. De Cesare	
<b>Prediction of Piezometric Levels at the Rock Concrete Interface Considering the Non-linearity of Permeability in the Foundations</b> . . . . .	793
M. de Granrut, B. Berthomé, and A. Simon	
<b>Direct Method for Dynamic Soil-Structure Interaction Based on Seismic Inertia Forces</b> . . . . .	807
D. Froio, A. U. Bariletti, M. Eusebio, R. Previtali, and E. Rizzi	

<b>The Influence of Microscopic Parameters on Deformation Properties of Rockfill Materials</b> .....	821
C. Ma, G. Zenz, E. J. Staudacher, and J. Yang	
<b>Cost Risk Assessment of 13 km Long Headrace Tunnel in the Himalayas</b> .....	833
F. Raggi, A. Tamburini, and L. Altarejos-Garcia	
<b>Identification of Dam Behavior by Means of Machine Learning Classification Models</b> .....	851
F. Salazar, A. Conde, and D. J. Vicente	
<b>Interpretation of Dam Monitoring Data Combining Visualisation Tools and Machine Learning. Eberlaste Dam Case Study</b> .....	863
F. Salazar, R. Kohler, A. Conde, and F. Landstorfer	
<b>Uncertainty Quantification and Reduction in the Structural Analysis of Existing Concrete Gravity Dams</b> .....	875
G. Sevieri, A. De Falco, and G. Marmo	
<b>A Non-destructive Parameter Identification for an Embankment Dam</b> .....	889
J. Toromanovic, H. Mattsson, J. Laue, and S. Knutsson	