ICOLD

INTERNATIONAL COMMISSION ON LARGE DAMS

CIGB ICOLD

ICOLD-BW 2019
9th-11th September
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

9 September 2019, Milan, Italy

Finite Element Analyses of a Concrete Gravity Dam

Investigation on static and dynamic behavior

RINA

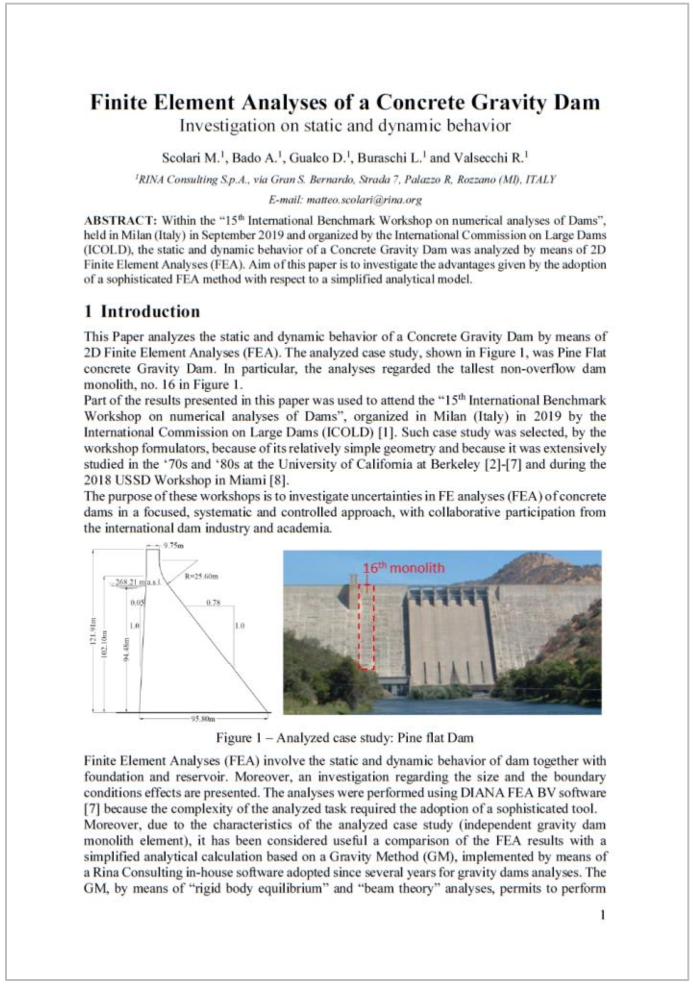
Scolari M., Bado A., Gualco D., Buraschi L. and Valsecchi R.

INTRODUCTION

Summary

In this presentation are going to be presented the most significant aspects:

- Presentation of the FEM MODEL
- ELEMENT SIZE effects
- BOUNDARY CONDITIONS effects
- FURTHER IMPROVEMENTS
- CONCLUSIONS


Finite Element Analyses of a Concrete Gravity Dam
Investigation on static and dynamic behavior

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ABSTRACT: Within the "15th International Benchmark Workshop on numerical analyses of Dams", held in Milan (Italy) in September 2019 and organized by the International Commission on Large Dams (ICOLD), the static and dynamic behavior of a Concrete Gravity Dam was analyzed by means of 2D Finite Element Analyses (FEA). Aim of this paper is to investigate the advantages given by the adoption of a sophisticated FEA method with respect to a simplified analytical model.

1 Introduction

This Paper analyzes the static and dynamic behavior of a Concrete Gravity Dam by means of 2D Finite Element Analyses (FEA). The analyzed case study, shown in Figure 1, was Pine Flat concrete Gravity Dam. In particular, the analyses regarded the tallest non-overflow dam monolith, no. 16 in Figure 1.
Part of the results presented in this paper was used to attend the "15th International Benchmark Workshop on numerical analyses of Dams", organized in Milan (Italy) in 2019 by the International Commission on Large Dams (ICOLD) [1]. Such case study was selected, by the workshop formulators, because of its relatively simple geometry and because it was extensively studied in the '70s and '80s at the University of California at Berkeley [2]-[7] and during the 2018 USSD Workshop in Miami [8].
The purpose of these workshops is to investigate uncertainties in FE analyses (FEA) of concrete dams in a focused, systematic and controlled approach, with collaborative participation from the international dam industry and academia.

Figure 1 – Analyzed case study: Pine flat Dam

Finite Element Analyses (FEA) involve the static and dynamic behavior of dam together with foundation and reservoir. Moreover, an investigation regarding the size and the boundary conditions effects are presented. The analyses were performed using DIANA FEA BV software [7] because the complexity of the analyzed task required the adoption of a sophisticated tool.
Moreover, due to the characteristics of the analyzed case study (independent gravity dam monolith element), it has been considered useful a comparison of the FEA results with a simplified analytical calculation based on a Gravity Method (GM), implemented by means of a Rina Consulting in-house software adopted since several years for gravity dams analyses. The GM, by means of "rigid body equilibrium" and "beam theory" analyses, permits to perform

1

INTRODUCTION

Italian Codes

N.T.C. 2018
Structures and **Infrastructures**

Supplemento ordinario alla "Gazzetta Ufficiale" n. 42 del 20 febbraio 2018 - Serie generale

Spediz. abb. post. - art. 1, comma 1
Legge 27-02-2004, n. 46 - Filiale di Roma

GAZZETTA UFFICIALE
DELLA REPUBBLICA ITALIANA

PARTE PRIMA — Roma - Martedì, 20 febbraio 2018 — SI PUBBLICA TUTTI I GIORNI NON FESTIVI

DIREZIONE E REDAZIONE PRESSO IL MINISTERO DELLA GIUSTIZIA - UFFICIO PUBBLICAZIONE LEGGI E DECRETI - VIA ARENULA, 70 - 00186 ROMA
AMMINISTRAZIONE PRESSO L'ISTITUTO POLIGRAFICO E ZECCA DELLO STATO - VIA SALARIA, 691 - 00138 ROMA - CENTRALINO 06-85081 - LIBRERIA DELLO STATO
PIAZZA G. VERDI, 1 - 00198 ROMA

N.T.D. 2014
Specific regulamentation on **Dam** design

8-7-2014 — GAZZETTA UFFICIALE DELLA REPUBBLICA ITALIANA — *Serie generale* - n. **156**

MINISTERO DELLE INFRASTRUTTURE E DEI TRASPORTI

DECRETO 26 giugno 2014.

Norme tecniche per la progettazione e la costruzione degli sbarramenti di ritenuta (dighe e traverse).

IL MINISTRO DELLE INFRASTRUTTURE E DEI TRASPORTI

DI CONCERTO CON

IL MINISTRO DELL'INTERNO

E

IL CAPO DEL DIPARTIMENTO DELLA PROTEZIONE CIVILE

di normative tecniche, anche per la verifica sismica ed idraulica, relative alle costruzioni, nonché per la progettazione, la costruzione e l'adeguamento, anche sismico ed idraulico, delle dighe di ritenuta, dei ponti e delle opere di fondazione e sostegno dei terreni, per assicurare uniformi livelli di sicurezza;

Considerato che, ai sensi del comma 1 dell'art. 5 del predetto decreto-legge 28 maggio 2004, n. 136, «ai fini dell'emanazione delle norme tecniche per la progettazione, la costruzione e l'adeguamento, anche sismico ed idraulico, delle dighe di ritenuta, il Ministro delle infrastrutture e dei trasporti acquisisce il parere tecnico del Registro Italiano Dighe», ora Direzione generale per le dighe, le infrastrutture idriche ed elettriche del Ministero delle infrastrutture e dei trasporti;

Considerato che il comma 2 del predetto art. 5 prevede che le norme tecniche di cui al comma 1 siano emanate con le procedure di cui all'art 52 del T.U. delle disposizioni legislative e regolamenti in materia di edilizia di cui

Appendix to **N.T.D. 2014** related to seismic analyses on dams (*July 2018*)

Ministero delle Infrastrutture e dei Trasporti
Dipartimento per le infrastrutture, i sistemi informativi e statistici
Direzione generale per le dighe e le infrastrutture idriche ed elettriche

VERIFICHE SISMICHE DELLE GRANDI DIGHE, DEGLI SCARICHI E DELLE OPERE COMPLEMENTARI E ACCESSORIE

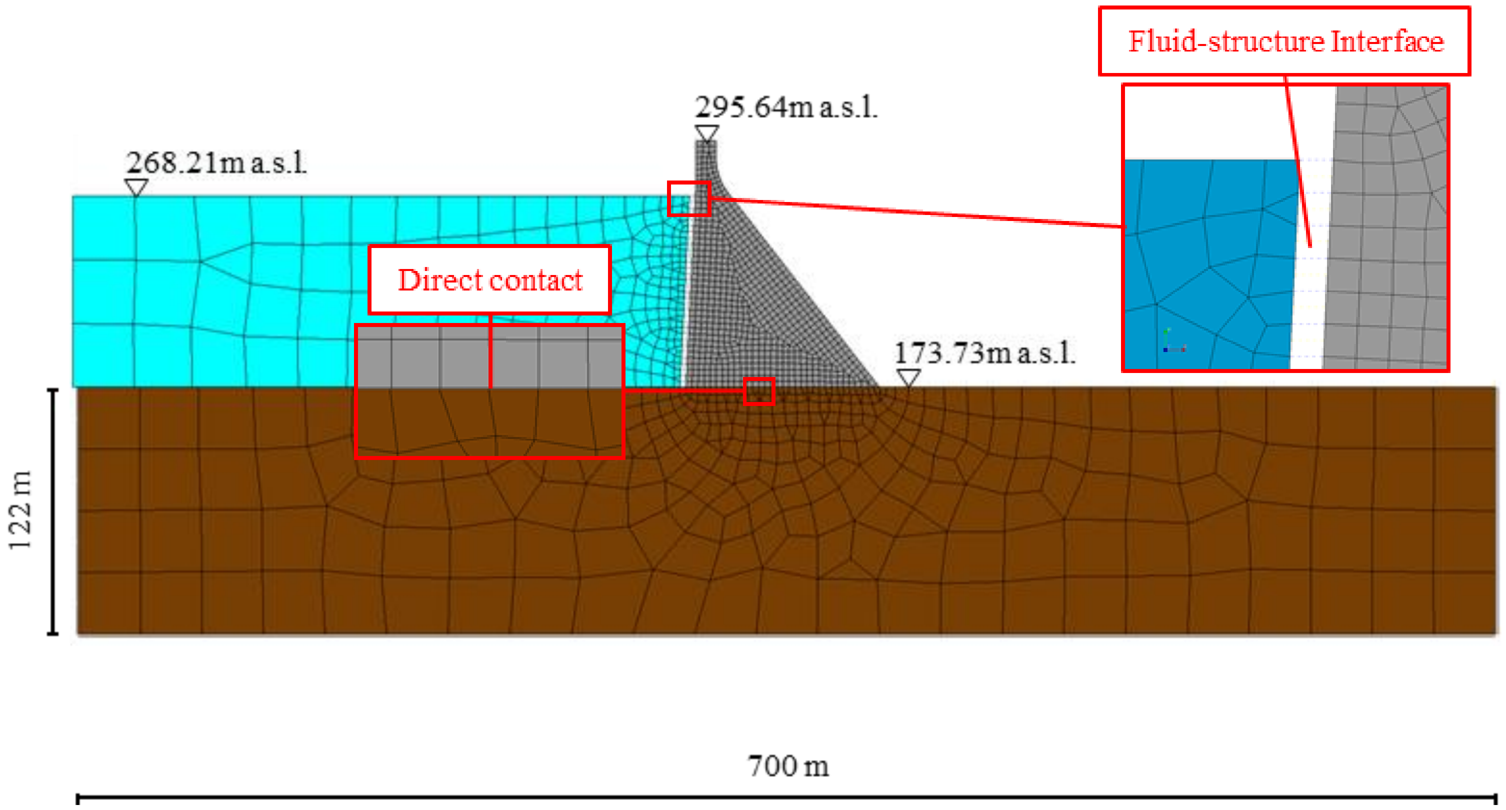
ISTRUZIONI PER L'APPLICAZIONE DELLA NORMATIVA TECNICA DI CUI AL D.M. 26.06.2014 (NTD14) E AL D.M. 17.01.2018 (NTC18)

For Dam assessment two different approaches should be followed:

- Serviceability Limit State (SLS) → evaluation of stresses over the dam body (σ, τ)
- Ultimate Limit State (ULS) → evaluation of global stability, sliding and overturning (N, V)

FEM MODEL

General description



- ➢Plain strain elements;
  - ➢Dam: 3 m wide elements;
  - ➢Foundation: 3 to 30 m wide elements;
- ➢Reservoir with fluid-structure interface to model the dynamic effect;
- ➢Direct contact between Dam and Foundation;
- ➢2% Rayleigh damping for dynamic analyses

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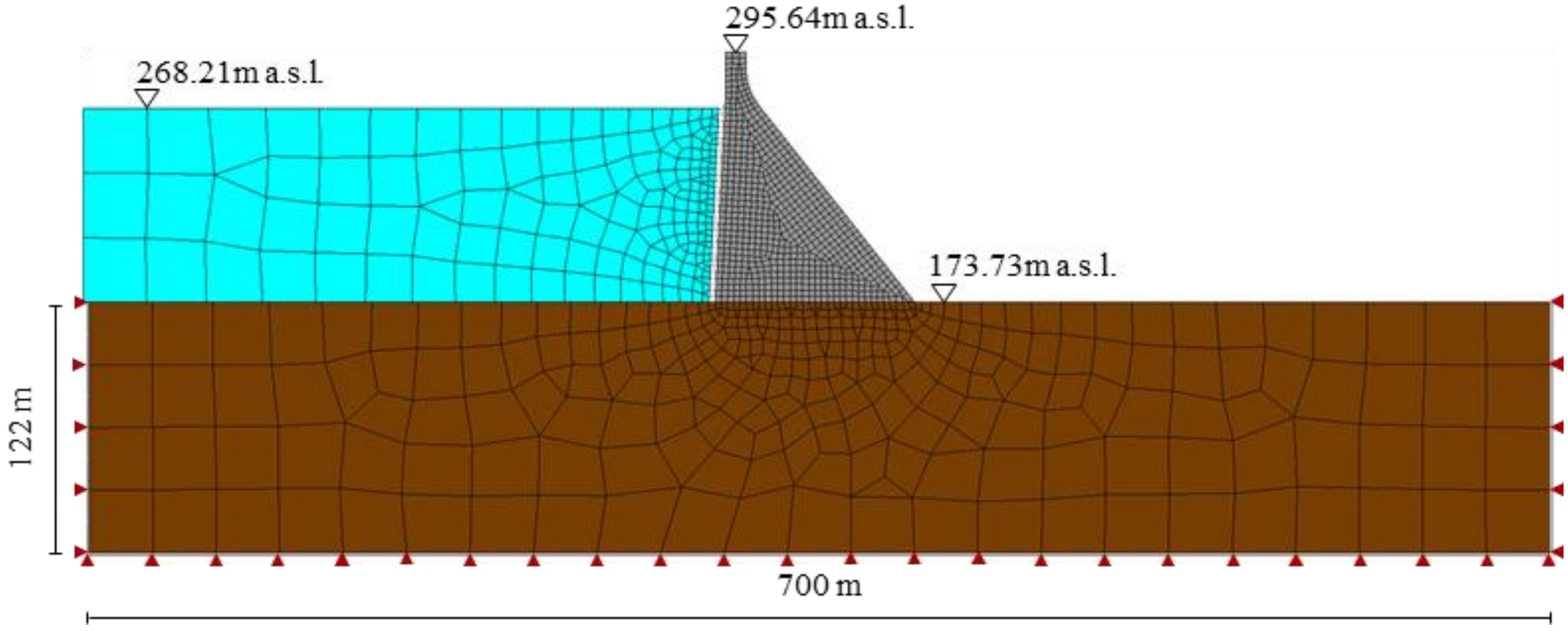
FEM MODEL

Static Boundary Conditions

Roller BCs were adopted at the external foundation edges

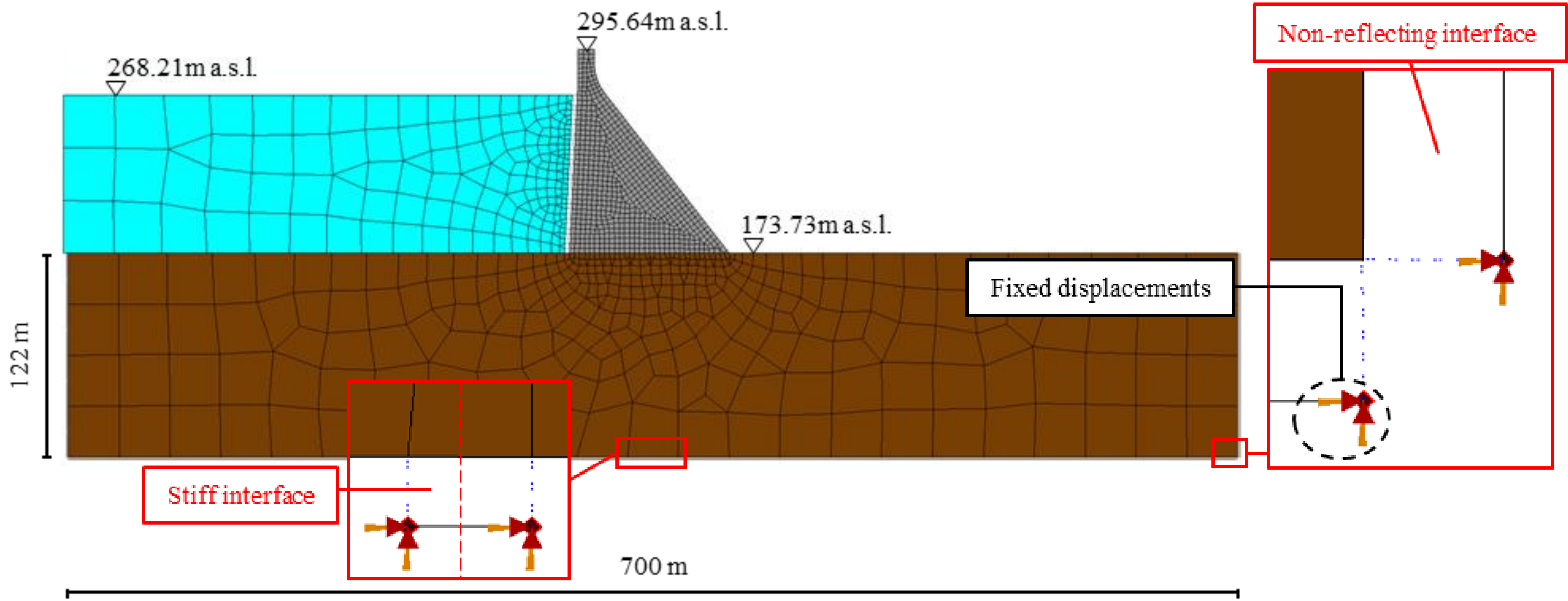


FEM MODEL

Dynamic Boundary Conditions

Non-reflecting interface were adopted at the external foundation edges

Interface properties	*Non-reflecting*	*Stiff*
Normal stiff. [N/m^3]	1	1
Shear stiff. [N/m^3]	1	$9.34\cdot10^9$
Normal damp. [Ns/m^3]	$7.86\cdot10^6$	$7.86\cdot10^6$
Shear damp. [Ns/m^3]	$4.82\cdot10^6$	$4.82\cdot10^6$



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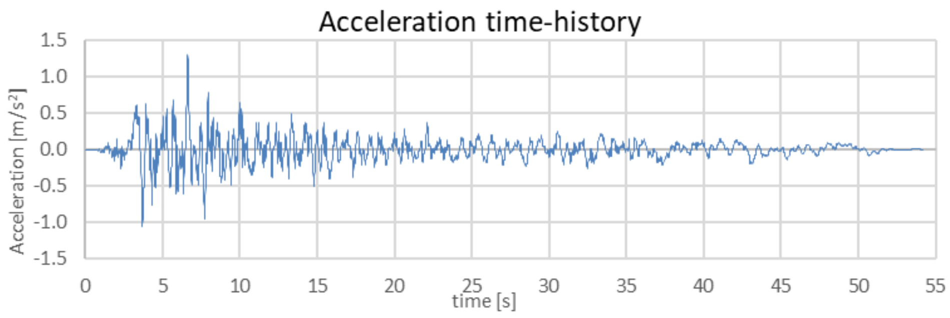
FEM MODEL

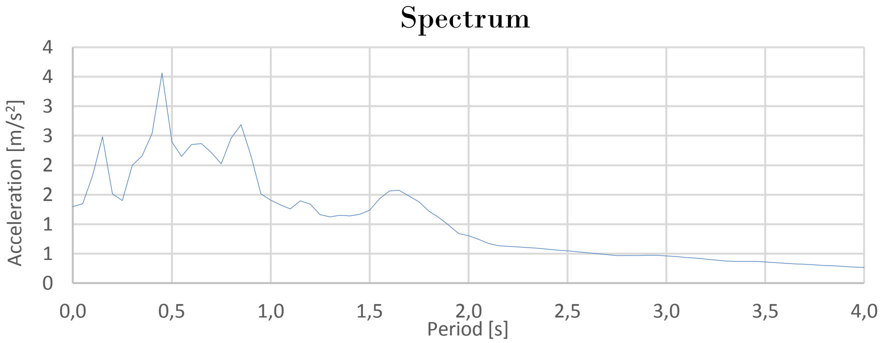
Two approaches were used for the *Static analysis*:

- Analytical: Gravity Model (GM)
- Numerical: Finite Element analyses (FEA)

Three approaches were used in *Dynamic analysis*:

- Analytical: Gravity Model (GM) pseudo-static
- Numerical: Finite Element analyses (FEA) pseudo-static
- Numerical: Finite Element analyses (FEA) with time-history





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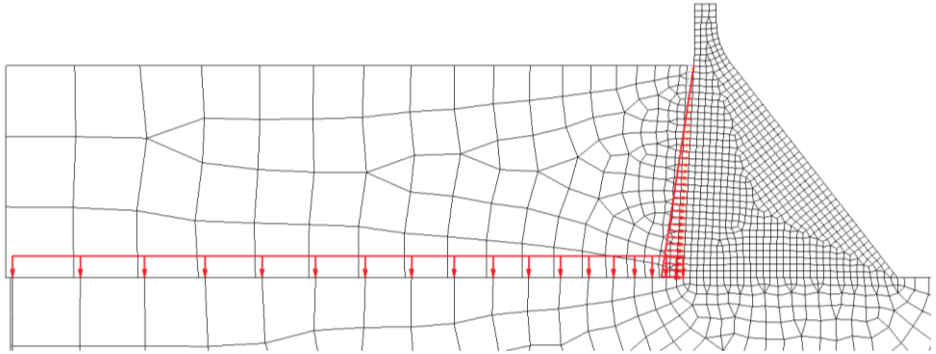
FEM MODEL

Static analysis

Loads

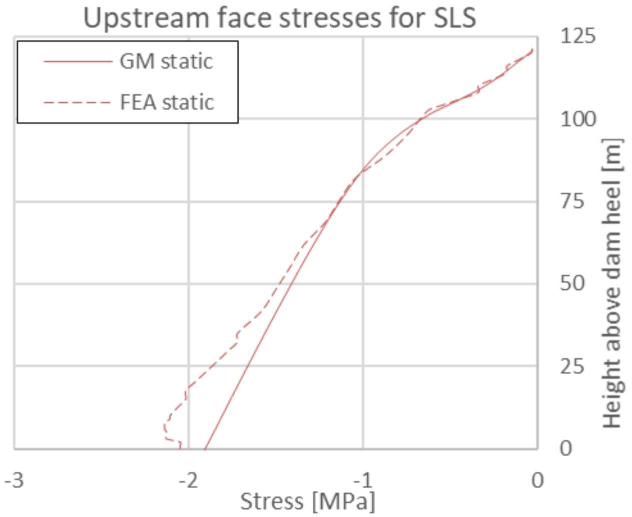
- Self-Weight (SW)
- Hydrostatic pressure (Pr268) on dam face and reservoir bottom



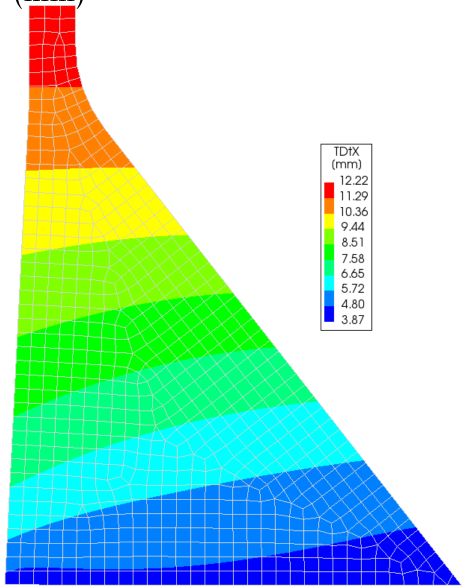
Results

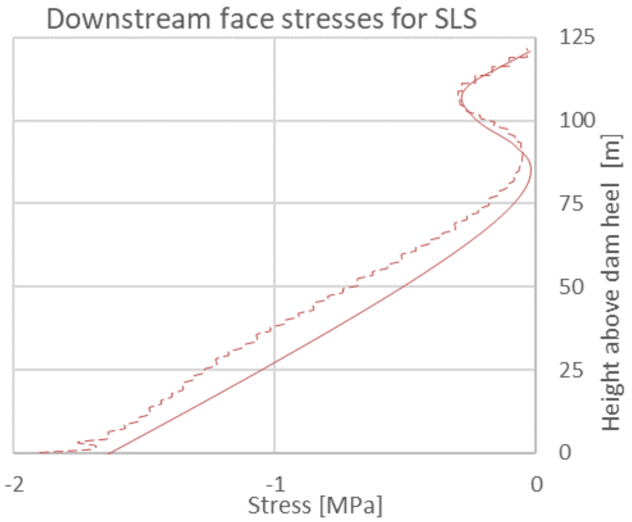
SLS

$$\begin{cases} \sigma_c \leq \sigma_{c,lim} \\ \sigma_t < \sigma_{t,lim} \end{cases}$$



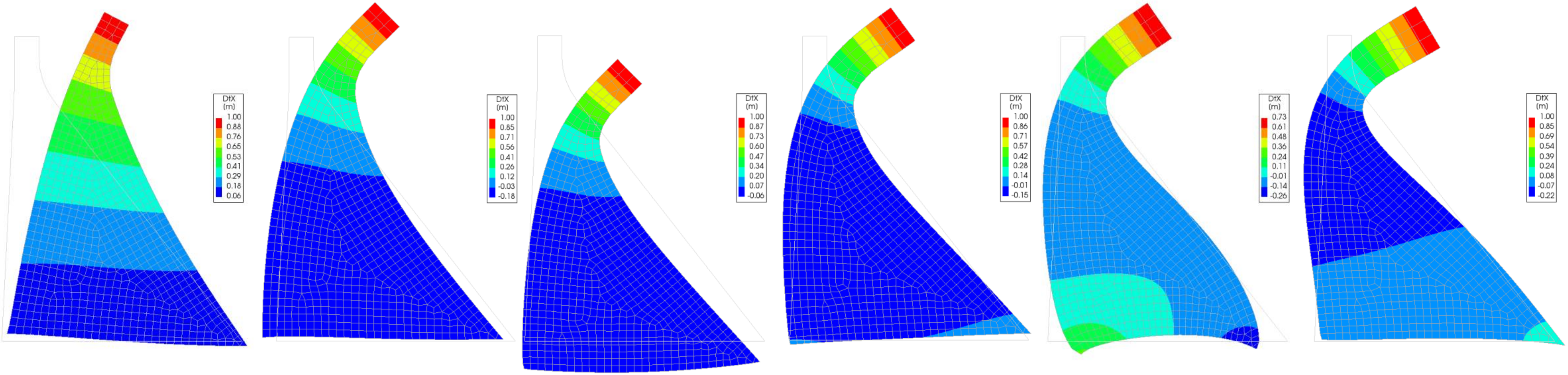
Horizontal displacement (mm)



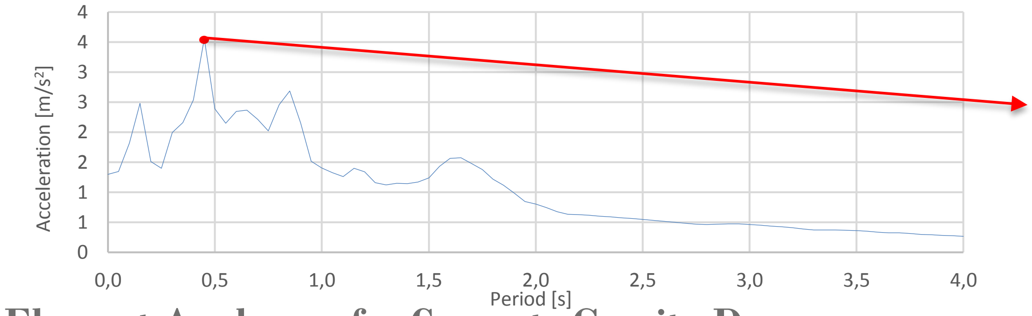


FEM MODEL

Modal analysis



Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
f = 2.31 Hz	f = 4.09 Hz	f = 4.87 Hz	f = 5.44 Hz	f = 5.94 Hz	f = 6.76 Hz
T= 0.43 sec	*T= 0.24 sec*	*T= 0.21 sec*	*T= 0.18 sec*	*T= 0.17 sec*	*T= 0.15 sec*



Pseudo-static analyses were run with the Spectral acceleration associated to the 1st Mode

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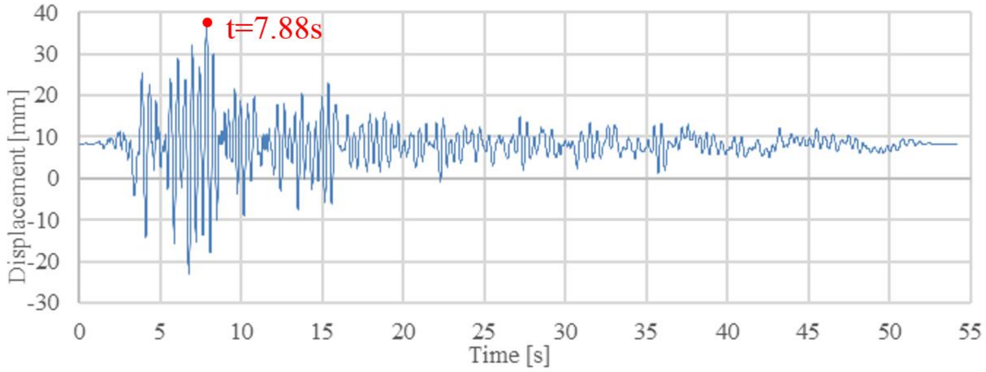
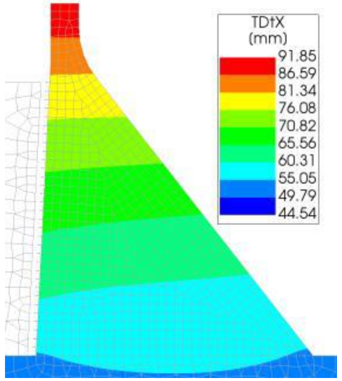
FEM MODEL

Dynamic analysis

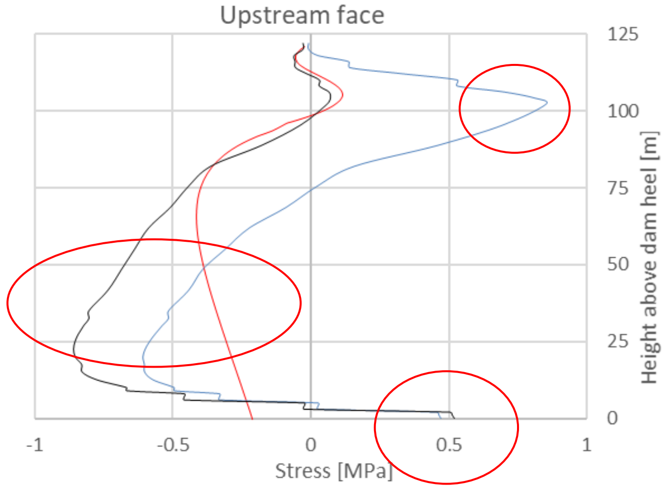
Displacements

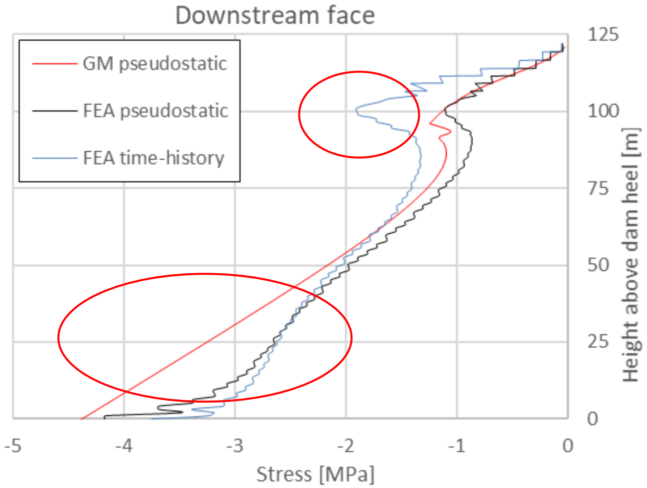




➢The seismic effect increased the horizontal displacement from ~8mm (static displacement) to ~37mm (dynamic displacement)

Stresses





➢Numerical analyses highlighted a peak of stresses at the contact dam/foundation;

➢ Numerical pseudo-static analyses highlighted lower stresses in the dam body with respect to analytical GM method;

➢ Time-history analyses highlighted peak of stresses in the upper part, due to modal shape;

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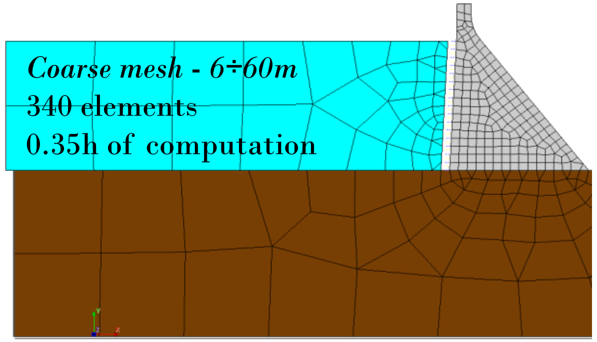
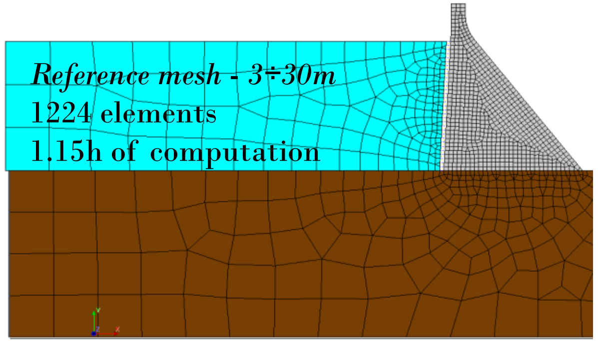
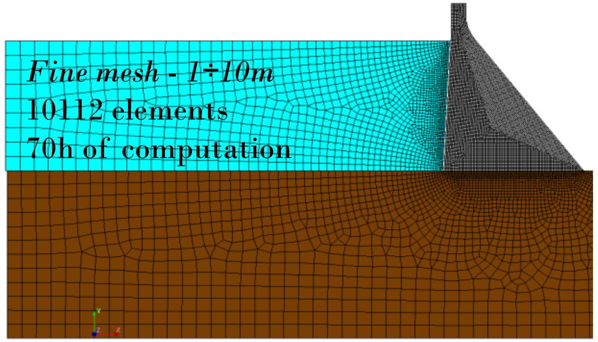
ELEMENT SIZE effect

Different mesh sets were used:

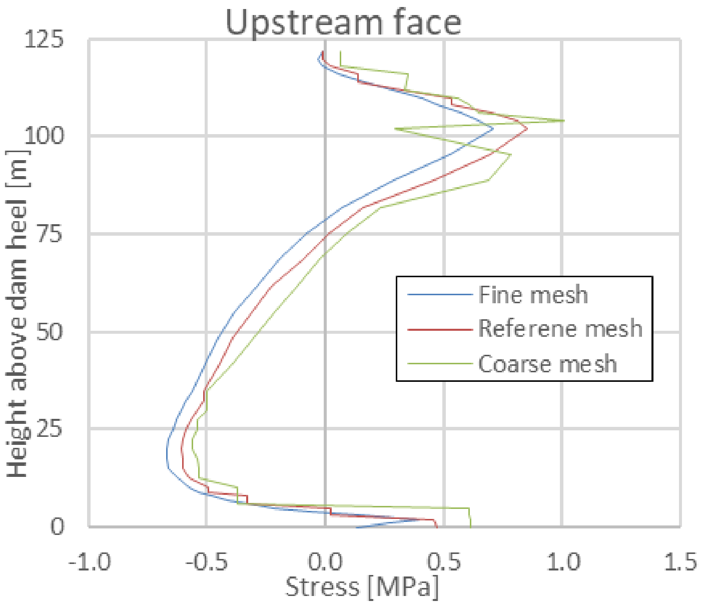
- Fine mesh (1 to 10m)
- Refernece mesh (3 to 30m)
- Coarse mesh (6 to 60m)

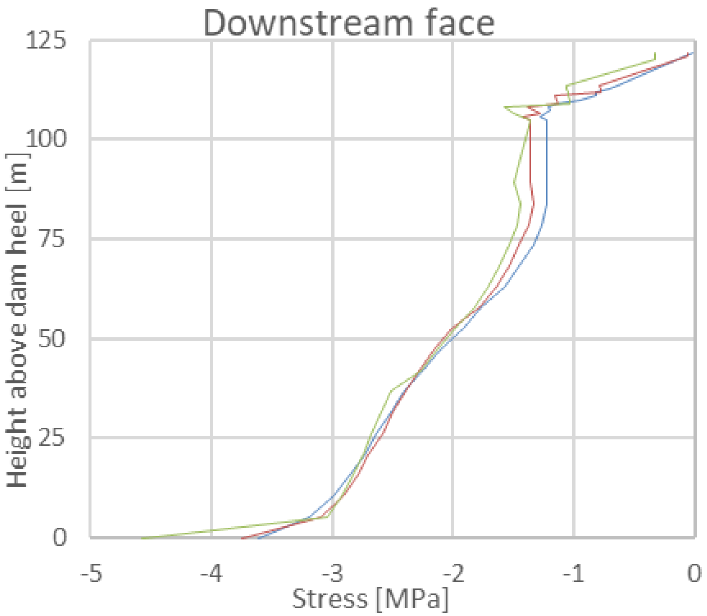






Stresses





- ➢Coarse mesh leads to less refined results with respect to the other ones;
- ➢Fine mesh leads to higher computational effort with respect to the other ones;

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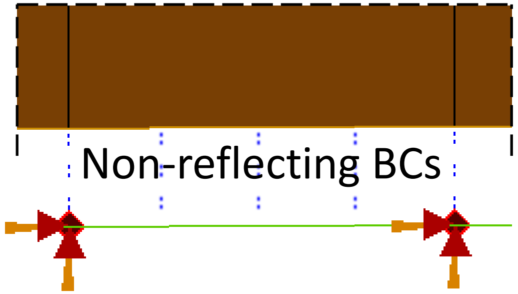
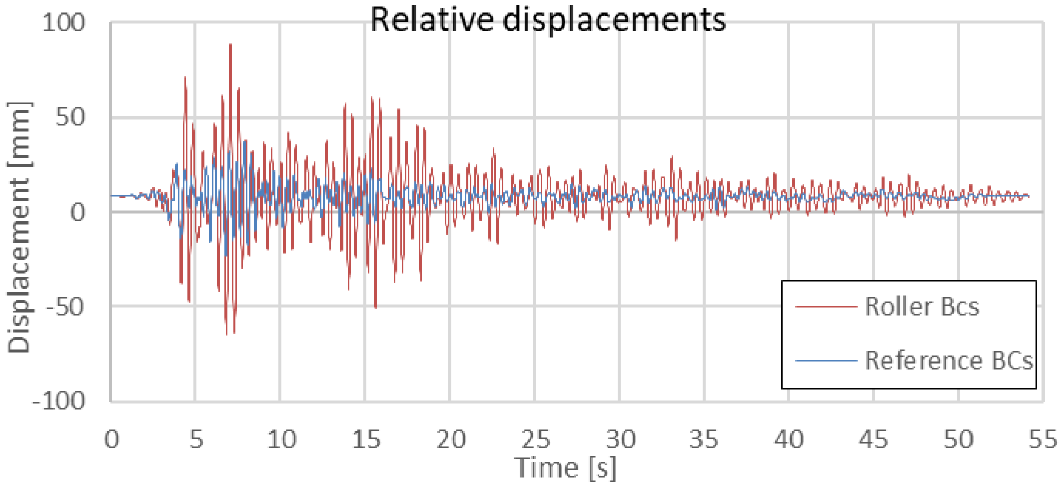
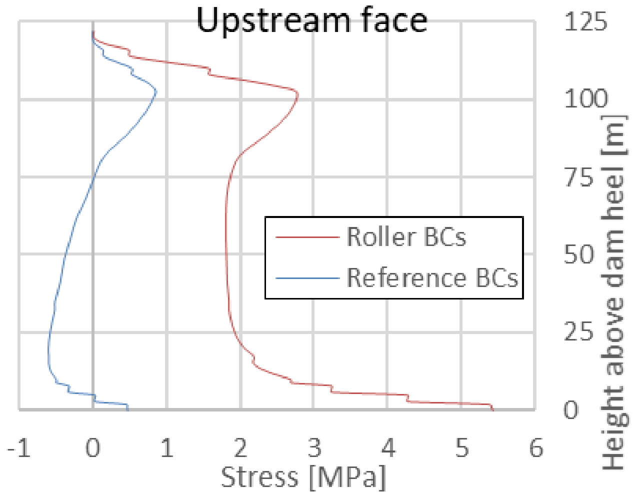
BOUNDARY CONDITION effect



Reference BCs:
Non-reflecting interface at the foundation edges

Roller BCs (same as static analysis):
Vertical restraint at the bottom edge and horizontal restraint at the side edges.





Simplified “Roller BCs” leads to much more higher horizontal displacements and stresses

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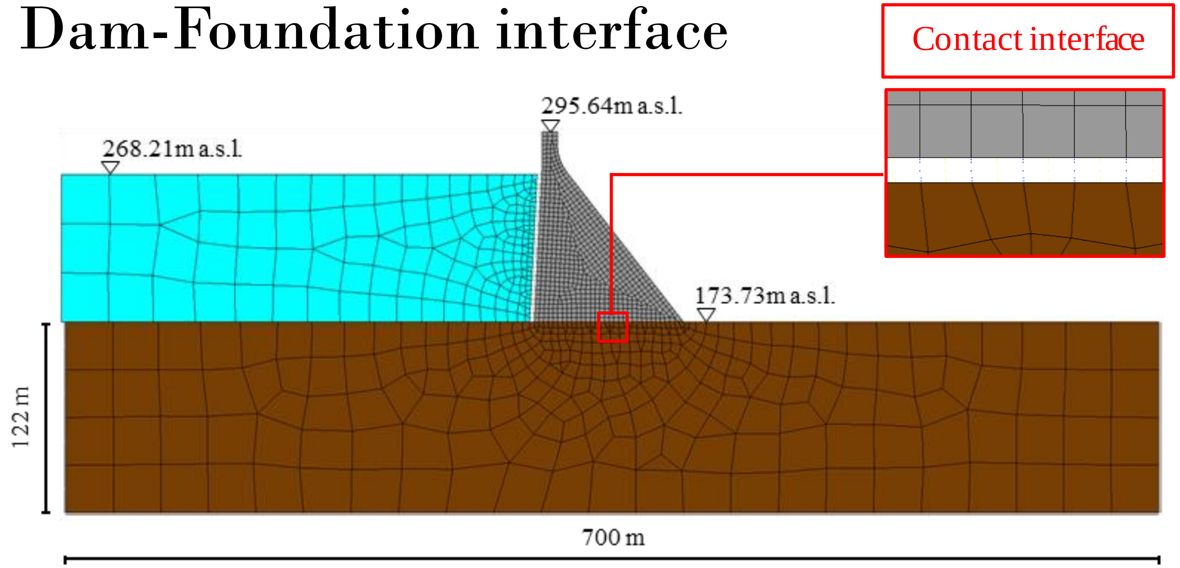
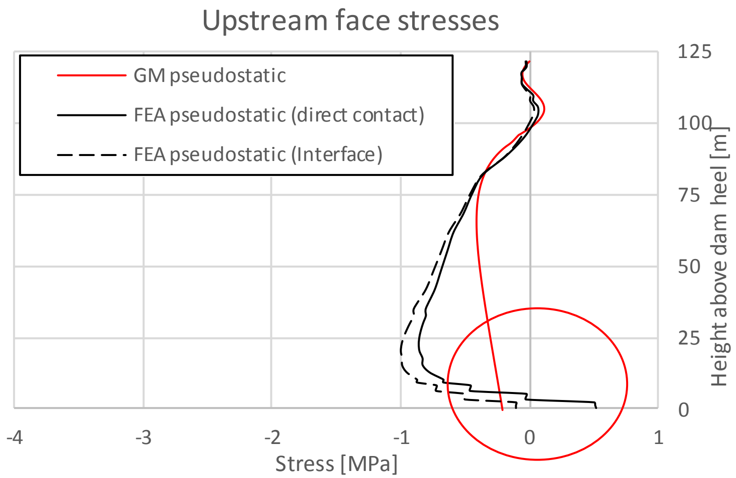
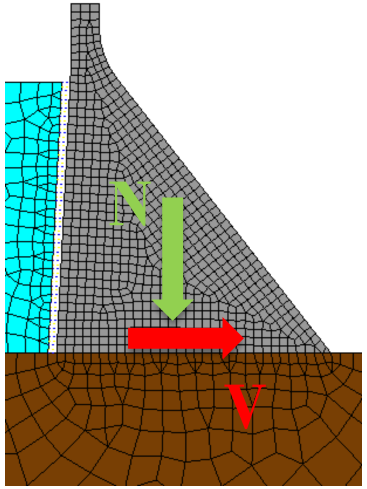
FURTHER IMPROVEMENTS

Dam-Foundation interface



Interface properties	Normal stiff. [N/m^3]	Shear stiff. [N/m^3]
Dam-Foundation Interface	$2.4 \cdot 10^9$ No-tension	$1.2 \cdot 10^9$ No-tension





- ➢Interface elements lead to a reduction of the stress peak at the dam-foundation contact

- ➢Possibility to adopt the model for the evaluation of global forces at the base of the dam

V/N	Static	Pseudo static
FEA	0.29	0.65
GM	0.31	0.78
Limit	0.75	

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CONCLUSIONS

Static behavior →	Numerical and Analytical model leads to similar results	→ Sophisticated method adoption is not necessary
Dynamic behavior →	Numerical analyses leads to more conservative results than Analytical one	→ Importance of investing on more sophisticated methods (such as FEA)
Boundary Conditions →	Fixed BCs leads to an amplification of input signal	→ Non-reflecting BCs is strongly recommended
Size-effect →	Join the computational advantages of a coarser mesh with the benefit in term of stresses evaluation given by a finer mesh.	→ Size equal to 2.5% of dam height

"…it makes sense to invest in a more advanced and time-consuming calculation if this can show that an existing structure is reliable enough and does not need strengthening."

Professor Joost C. Walraven, TU DELFT

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THANK YOU FOR YOUR ATTENTION

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