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A researcher's perspective on modelling unbounded domains for earthquake analysis of dams

Arnkjell Løkke

Norwegian Univ. of Science and Technology (NTNU)
University of California, Berkeley

Introduction

Focus of my research

Collaboration between UCB and NTNU

- Supervisor: Professor Anil K. Chopra, UC Berkeley
- Co-supervisor: Amir Kaynia, NTNU

Objective to formulate and validate accurate procedures for nonlinear response history analysis of concrete dams

- Start with rigorous (theoretical) derivation, then do approximations where necessary
- Procedure for both 2D (gravity) and 3D (arch) dam systems


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Direct finite element method for nonlinear analysis of semi-unbounded dam–water–foundation rock systems

Arnkjell Løkke[1] and Anil K. Chopra[2,*,†]

[1] *Department of Structural Engineering, Norwegian University of Science and Technology, Trondheim 7491, Norway*
[2] *Department of Civil and Environmental Engineering, University of California Berkeley, Berkeley, CA 94720, USA*

SUMMARY

A direct finite element method is presented for nonlinear earthquake analysis of interacting dam–water–foundation rock systems. The analysis procedure applies viscous damper absorbing boundaries to truncate the semi-unbounded fluid and foundation-rock domains and specifies at these boundaries effective earthquake forces determined from the design ground motion defined at a control point on the free surface. The analysis procedure is validated numerically by computing the frequency response functions and transient response of an idealized dam–water–foundation rock system and comparing with results from the substructure method. Because the analysis procedure is applicable to nonlinear systems, it allows for modeling of concrete cracking, as well as sliding and separation at construction joints, lift joints, and at concrete–rock interfaces. Implementation of the procedure is facilitated by commercial finite element software with nonlinear material models that permit modeling of viscous damper boundaries and specification of effective earthquake forces at these boundaries.

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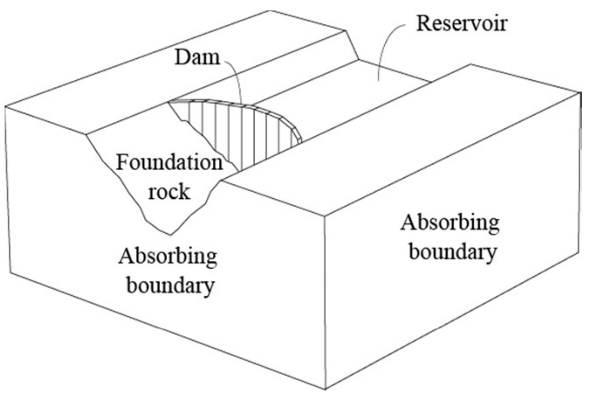
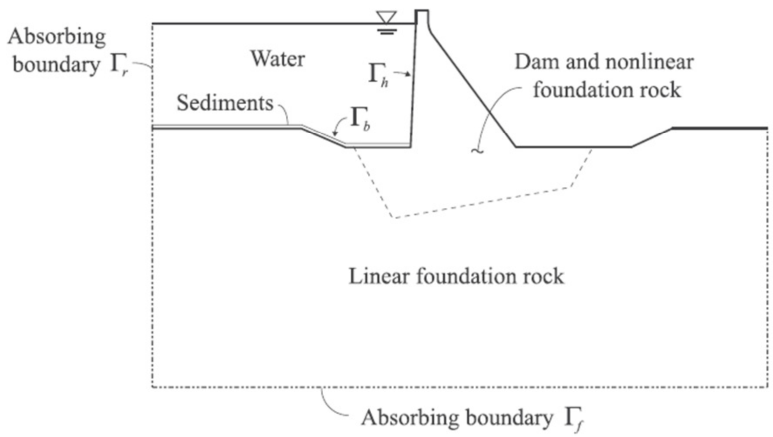
KEY WORDS: nonlinear earthquake analysis; absorbing boundaries; dam-water-foundation rock interaction; concrete dams





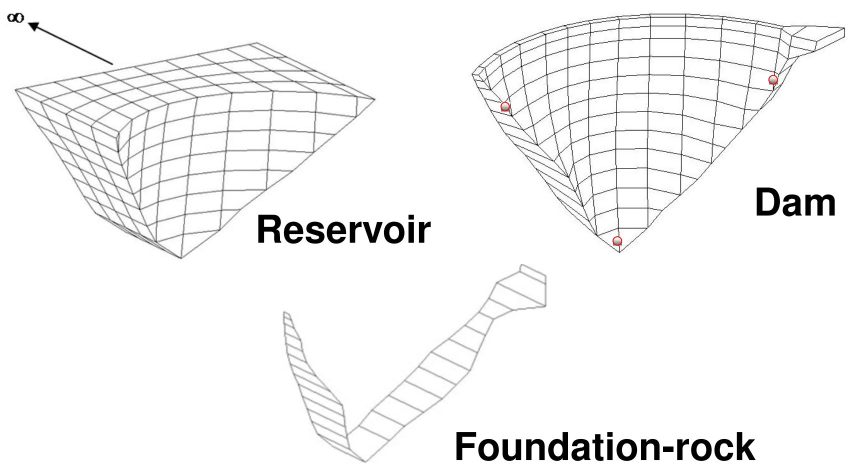
Response history analysis of dams is a complex problem

- **Semi-unbounded domains**
  - Foundation-rock and reservoir
- **Interaction effects**
  - Between dam, water, foundation-rock
- **Spatially varying ground motion**
  - How to obtain this motion?
- **Nonlinear mechanisms**
  - Concrete cracking
  - Sliding and separation at joints and interfaces

Available methods today

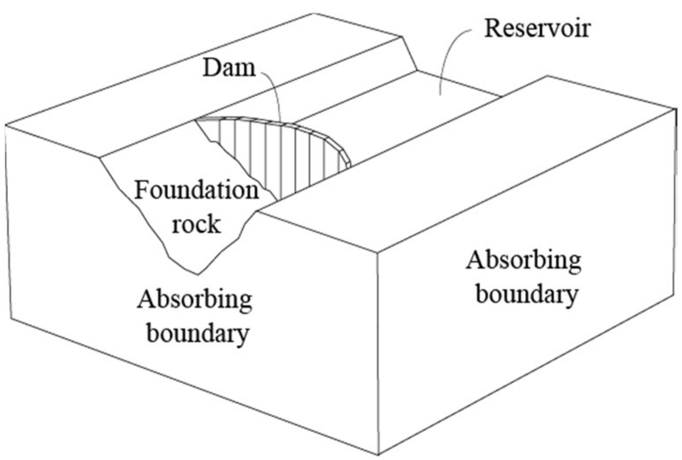
Neither offer a fully satisfactory solution

Substructure method (frequency domain)



- **Special-purpose software**
  - EAGD84 / EACD-3D
- **Rigorous (analytical) treatment of unbounded domains**
- **Restricted to linear analysis**

Direct FE method (time domain)



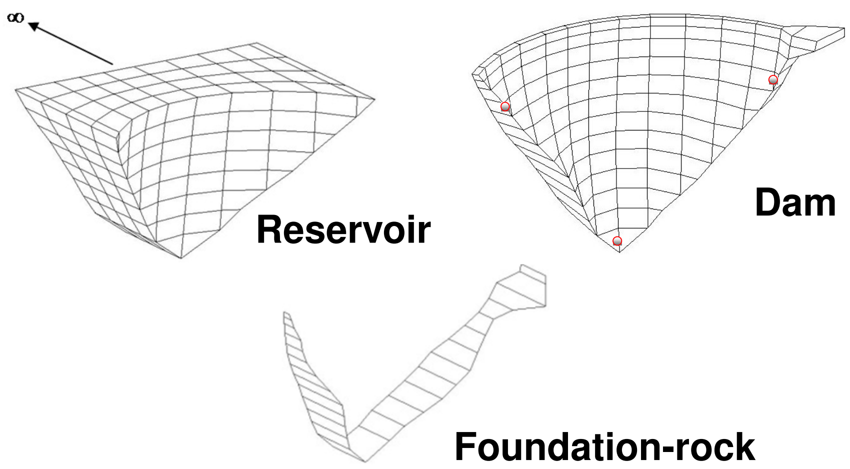
- **Commercial FE software**
  - Abaqus, LS-DYNA, etc.
- **Nonlinear analysis**
- **Often unsatisfactory models for unbounded domains**

Available methods today

Neither offer a fully satisfactory solution

Focus of today's presentation

Substructure method (frequency domain)



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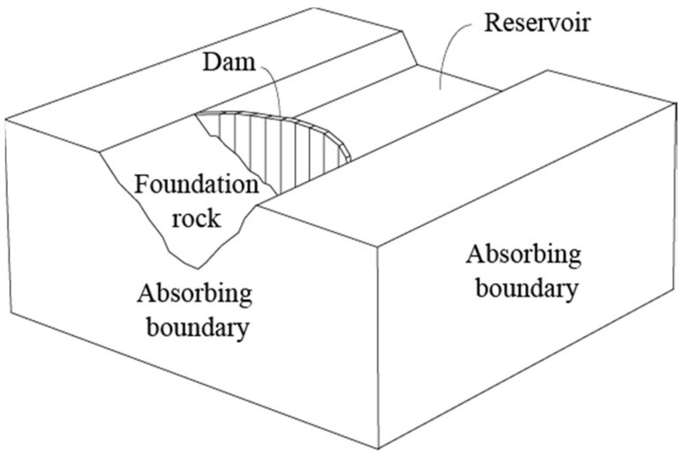
Direct FE method (time domain)



- **Commercial FE software**
  - Abaqus, LS-DYNA, etc.
- **Nonlinear analysis**
- **<u>Often unsatisfactory models for unbounded domains</u>**

Outline of presentation

1. Theory: Modelling of unbounded domains
2. Results for 2D gravity dam system
3. Summary and recommendations

Objective is to highlight pitfalls and provide recommendations for modelling unbounded domains

Theory: Modelling of unbounded domains

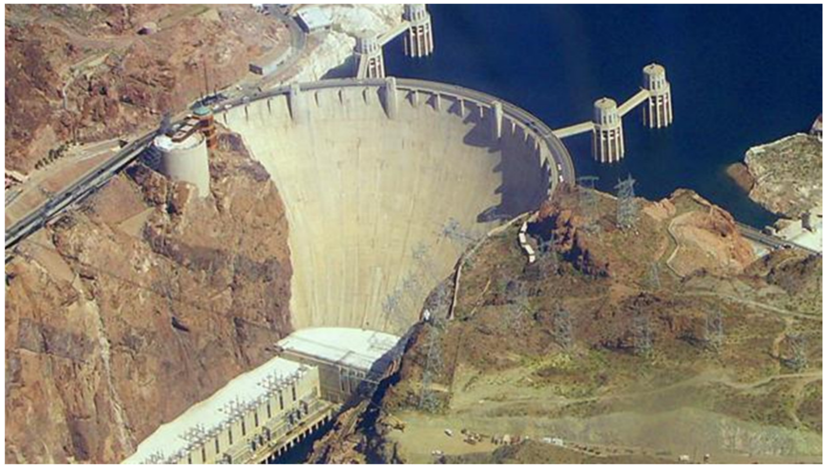
Unbounded domains requires special attention

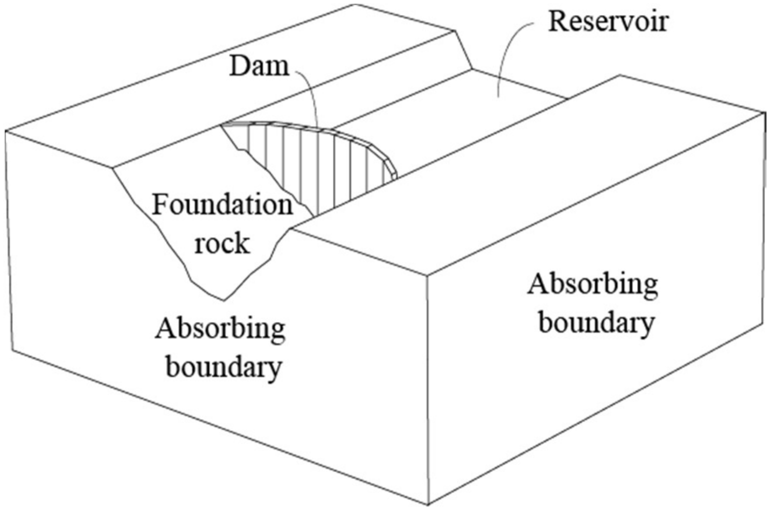
Issue 1: Absorbing boundaries must be applied to model

Unbounded domains must be truncated and wave-absorbing boundaries applied at these truncations

Need to satisfy radiation condition at the boundary:

- e.g. $\frac{\partial u}{\partial x} = \frac{1}{c}\frac{\partial u}{\partial t}$ in the x-direction





Unbounded domains requires special attention

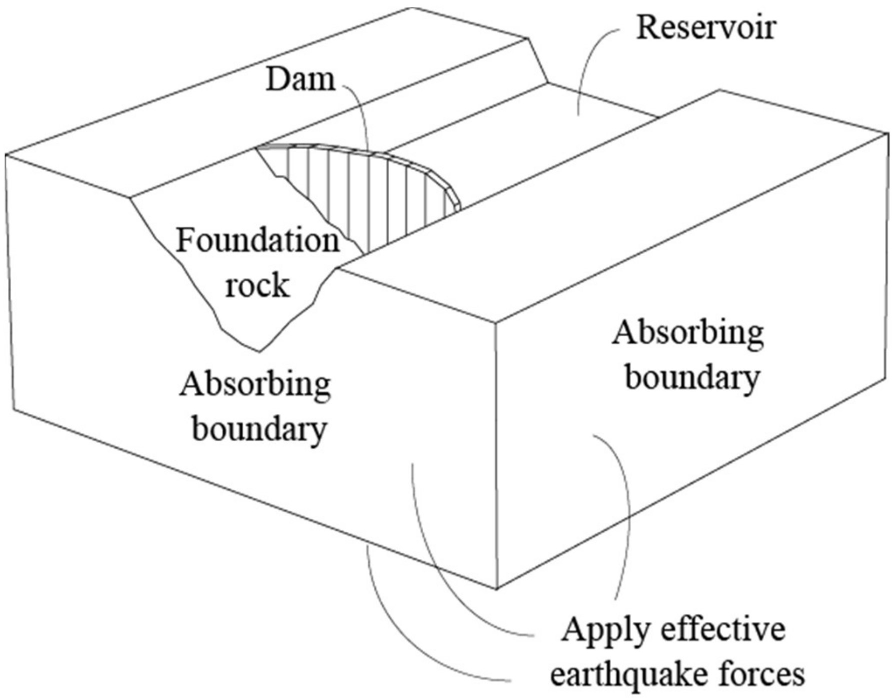
Issue 2: Seismic input must be specified as Effective Earthquake Forces

Prescribing displacements at the model truncations will lead to a reflective boundary

Instead, Effective Earthquake Forces must be applied at the boundaries or in a layer of elements inside of boundaries

Several formulations available, e.g.:

- Traction input (Zienkiewicz, Wolf)
- Domain Reduction Method (Bielak et. al.)



Choosing the type of absorbing boundary

Generally three types of boundary conditions

1. Elementary boundary conditions
2. Consistent boundary conditions
3. Local boundary conditions

Elementary boundaries does not satisfy radiation condition

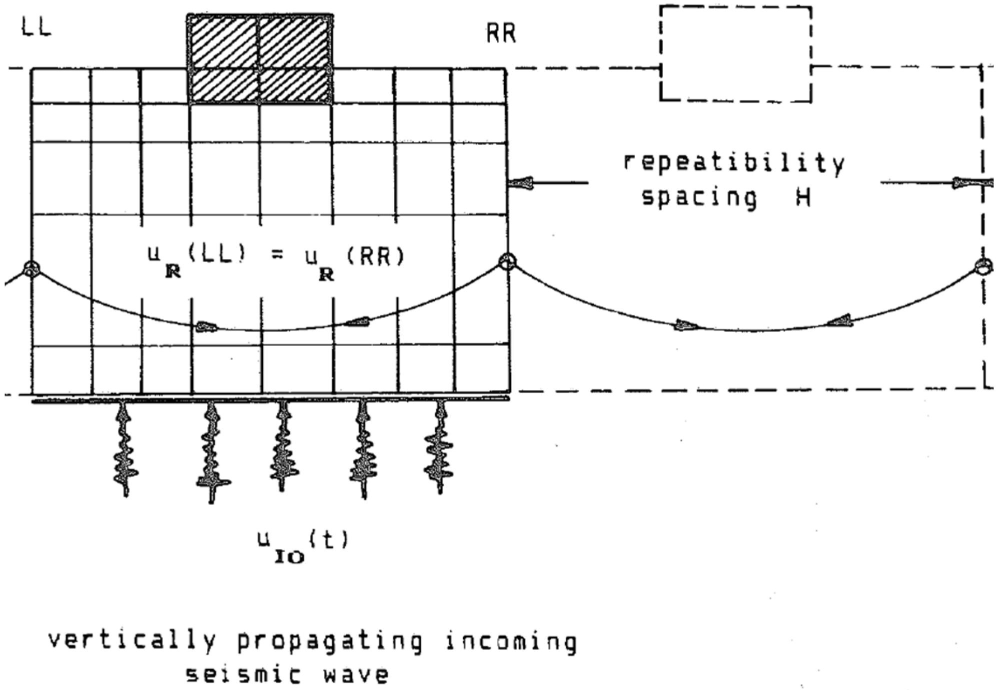
1 Elementary boundaries

Fixed ($u = 0$) or free ($\sigma = 0$) boundaries, or a combination

<u>Does not</u> satisfy radiation condition -> no energy absorption

"Tied" boundaries is a variation of elementary boundaries

- Sometimes used for soil analysis
- Enforces 1D conditions
- Not appropriate for stiff materials such as rock



Tied boundaries (Figure from Zienkiewicz, 1989[1])

1. Zienkiewicz OC, Bicanic N, Shen FQ. Earthquake Input Definition and the Transmitting Boundary Conditions. In: Advances in Computational Nonlinear Mechanics, 1989.

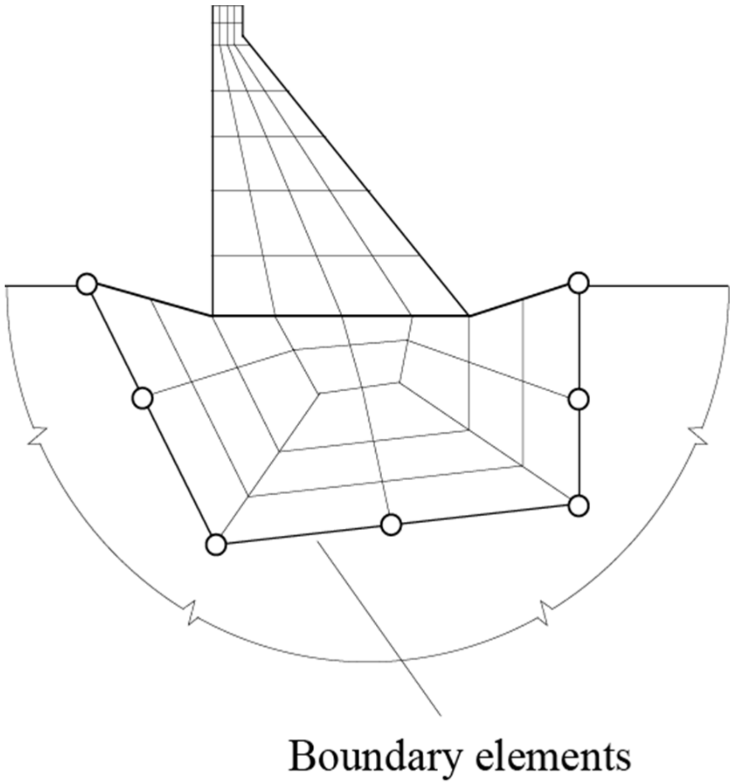
Consistent boundaries are exact, but cumbersome to implement in time domain

2 Consistent boundaries

Global formulations that satisfy <u>exactly</u> the radiation condition

Frequency dependent formulations:

- e.g. Boundary Element Method
- Useful for steady-state problems
- Cumbersome to implement for transient time domain analyses



Local boundaries most commonly used for transient time-domain analysis

3 **Local boundaries**

Local formulations that satisfy <u>approximately</u> the radiation condition

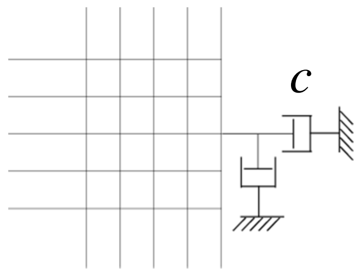
Error can be made sufficiently small by proper selection of parameters and domain size

Vast number of BCs available, e.g.:

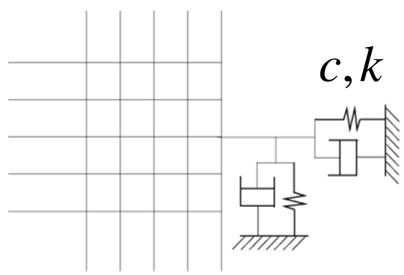
- Viscous dampers
- Viscous-spring (cone)
- PML
- Paraxial, Multi-Directional, Double-Asymptotic, +++

Simple

Viscous damper

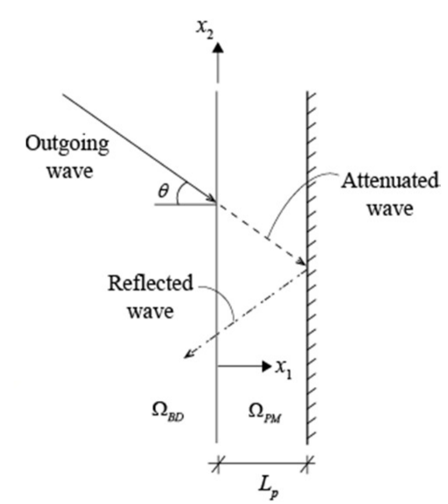


Viscous-spring (cone)



Advanced

Perfectly Matched Layer (PML)



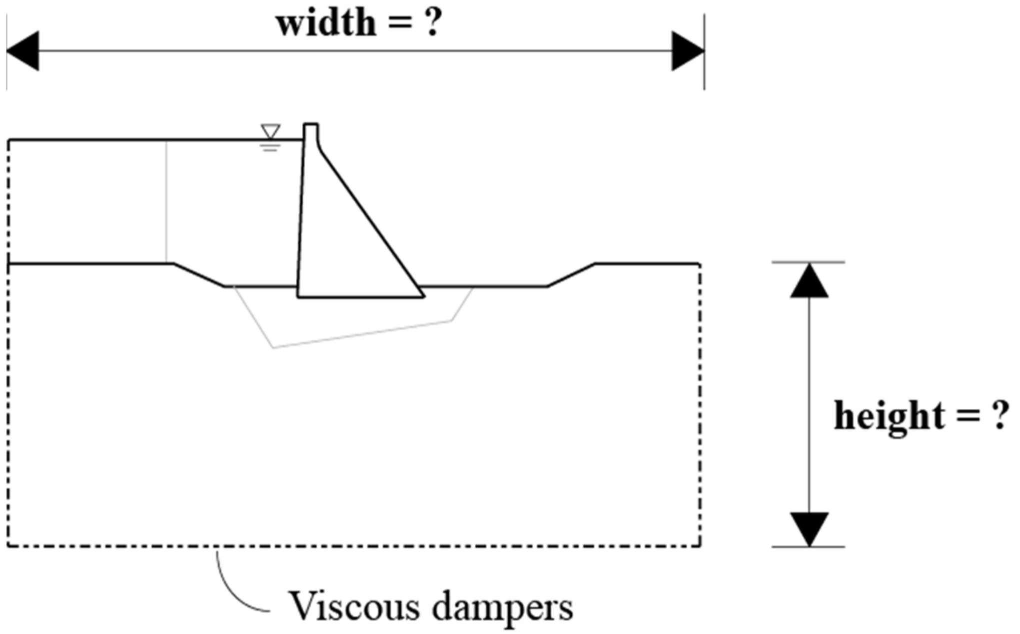
Although among the simplest, the viscous damper is still most commonly used

Viscous damper is accurate enough for most cases

- But needs “large” domain sizes

We selected to use the viscous damper for 2D / 3D analysis of concrete dams

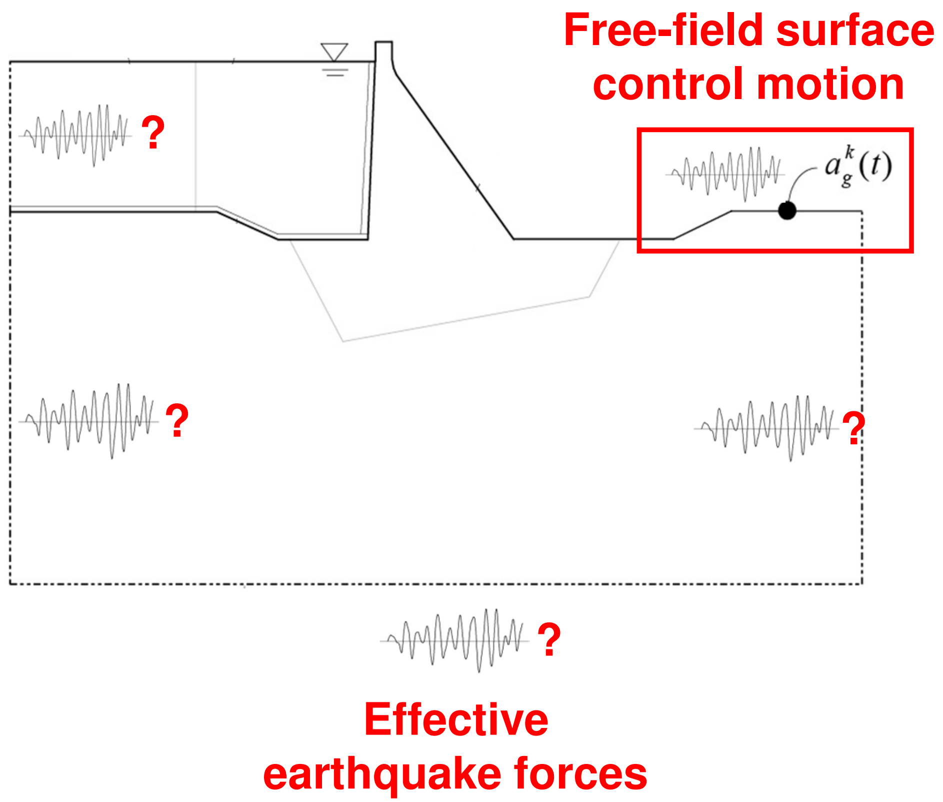
- Superior availability in FE codes



The key question is:
How big of a domain is required?

Second issue: How to specify the seismic input?

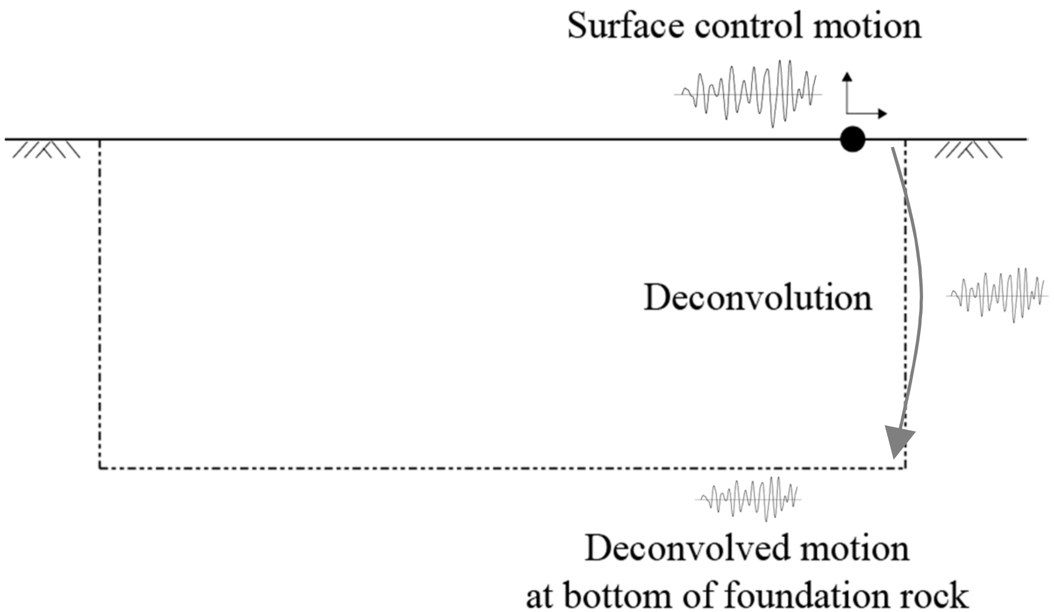
- Earthquake motion usually specified as free-field ground motion at the surface
- However, we need to apply forces (tractions) to the model to allow for absorbing boundaries



Need a method to apply effective earthquake forces to the model

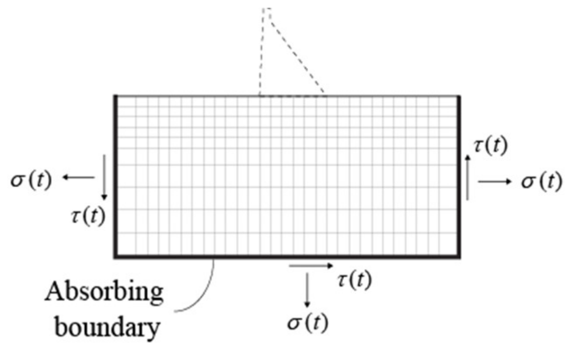
Deconvolution to obtain free-field motion at depth

- Free-field control motion specified at ground surface
- Surface motion is deconvolved to obtain the motion at depth (assumes vertically propagating waves)
- If material damping in rock is <u>neglected</u> – can approximate deconvolution by taking ½ of surface motion



Two types of methods are available to apply forces using free-field motion as input

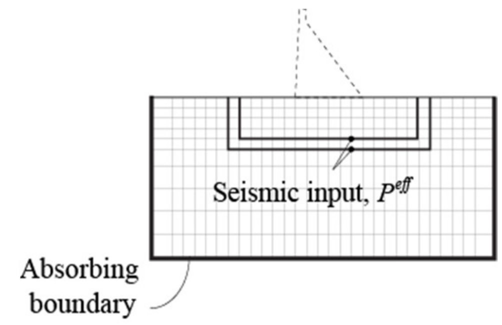
Traction input method



$$\sigma(t) = \sigma^0(t) + \rho V \dot{u}^0(t)$$

- Forces applied directly to boundaries
- Formulation depends on the BC used
- “Only” vertically propagating waves
- Can be implemented using “free-field” boundary element (FLAC, Plaxis, Code_Aster, ++)

Domain Reduction Method

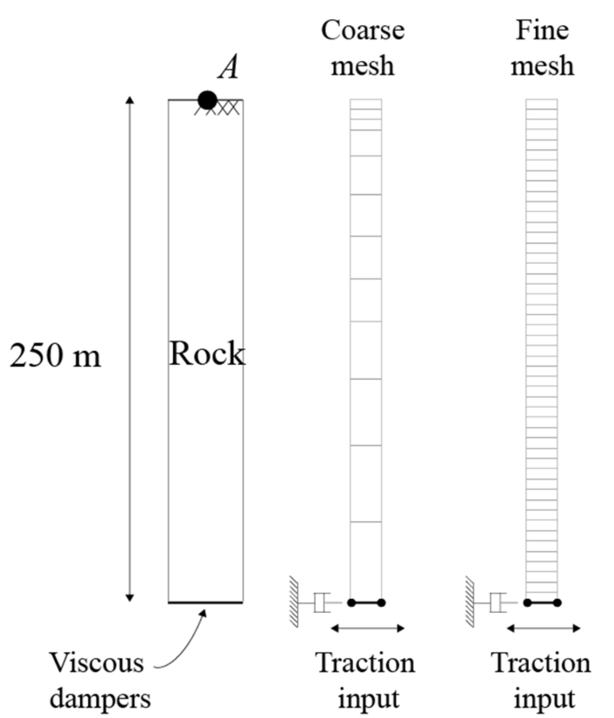


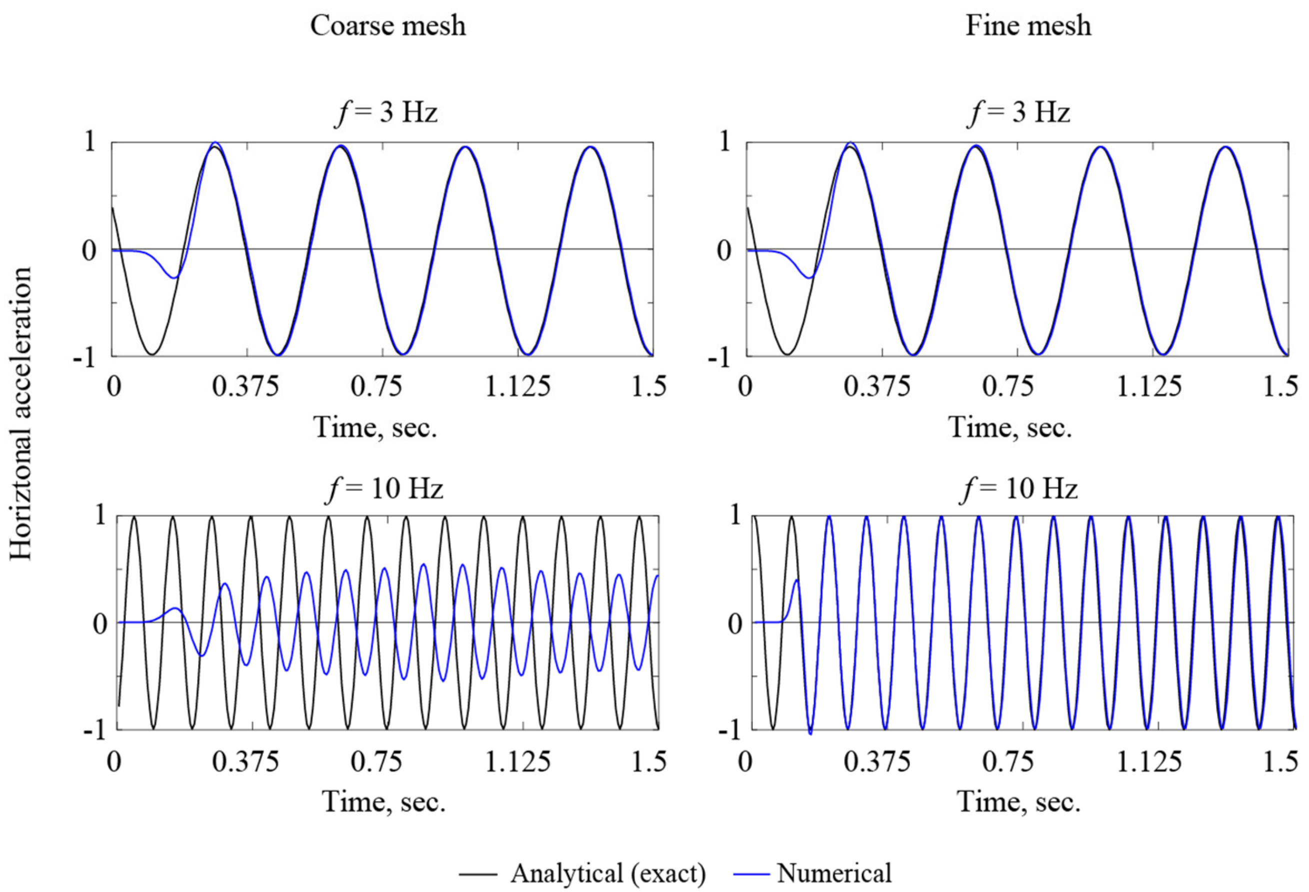
$$P^{eff} = \begin{Bmatrix} -M_{be}\ddot{u}_e^0 - C_{be}\dot{u}_e^0 - K_{be}u_e^0 \\ M_{eb}\ddot{u}_b^0 + C_{eb}\dot{u}_b^0 + K_{eb}u_b^0 \end{Bmatrix}$$

- Forces applied in single layer of elements
- Formulation decoupled from the BC used
- Can handle a full 3D wave field
- Clearly the most promising, but needs to be implemented in FE codes to be available (so far only LS-DYNA)

Possible pitfall: Need to ensure sufficient mesh density to propagate high frequencies

1D rock halfspace



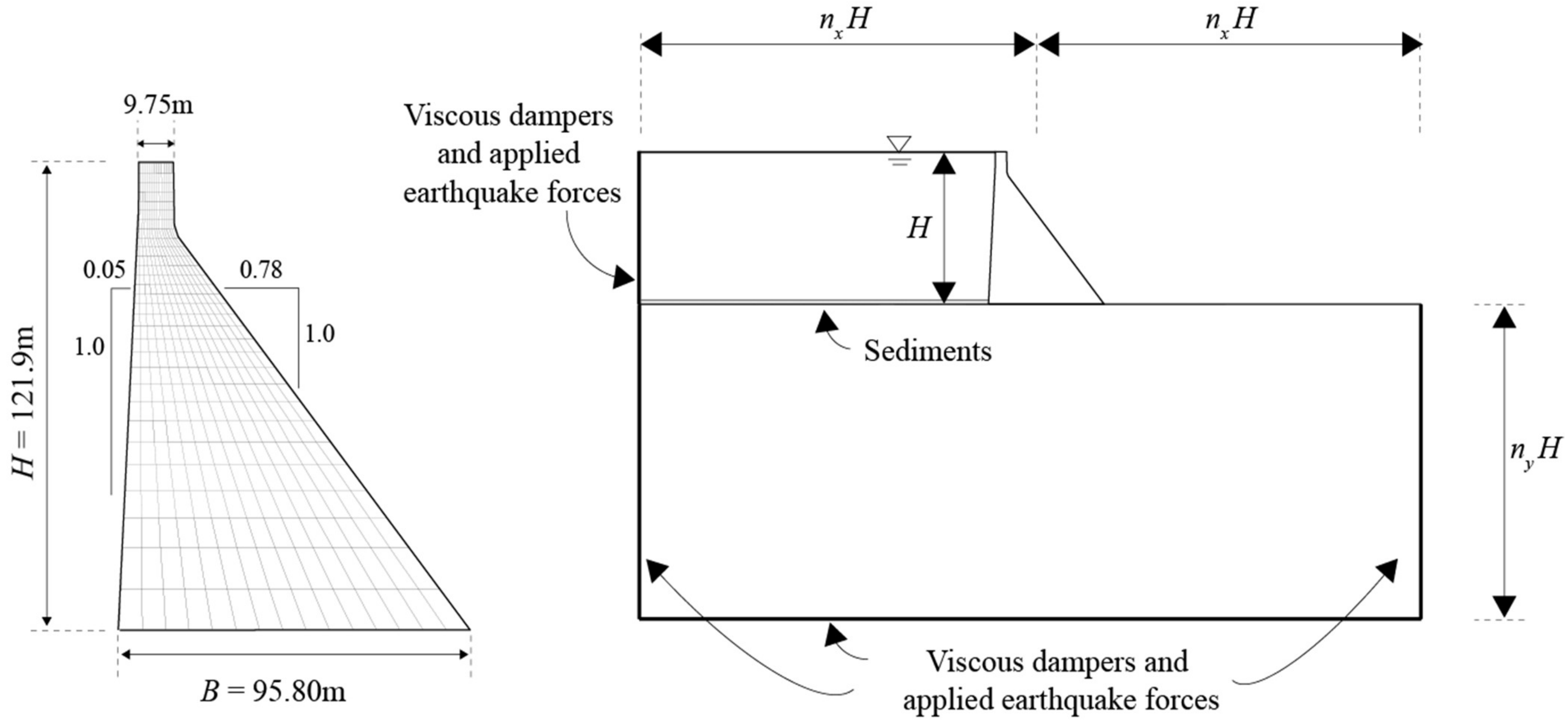


Should have 8-10 elements per shortest wavelength considered in analysis (Kuhlemeyer & Lysmer, 1973[1])

1. Kuhlemeyer, R.L. & Lysmer, J., 1973. Finite element method accuracy for wave propagation problems. *Journal of the Soil Mechanics and Foundations Division*, 99(5), pp.421–427.

Response results for a gravity dam

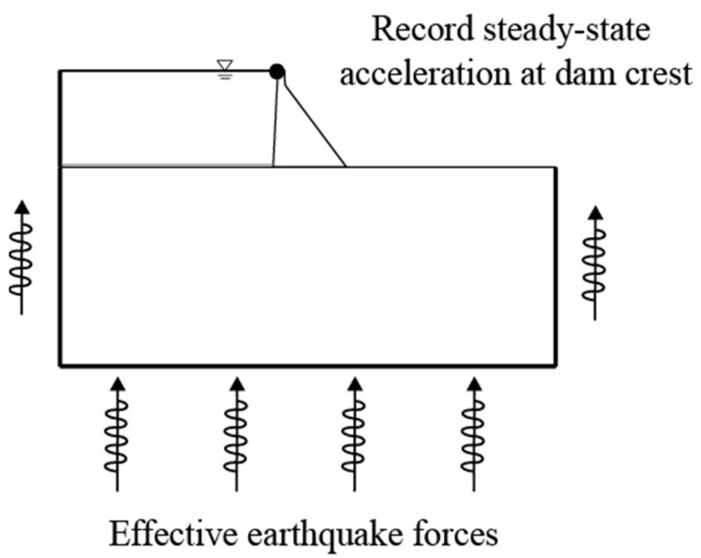
Pine Flat Dam chosen for analysis



- **Geometry and material properties typical of concrete dams**
- **Repeated analysis for different domain sizes**
  - Investigate accuracy of viscous dampers
  - Semi-analytical solutions (EAGD-84) used as benchmark

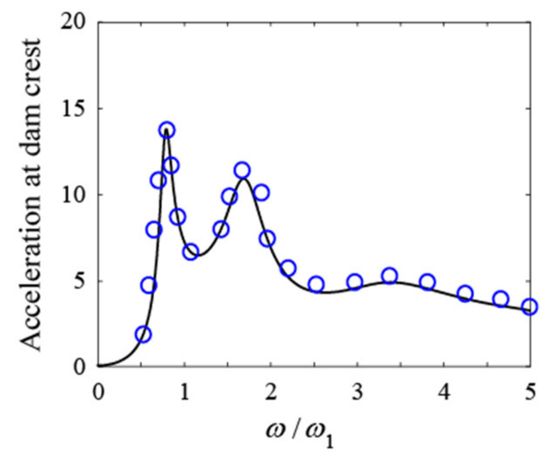
Response results will be presented as frequency response functions for crest acceleration

Analysis for single frequency



- Apply harmonic excitation as effective earthquake forces
- Compute steady-state acceleration at crest of dam

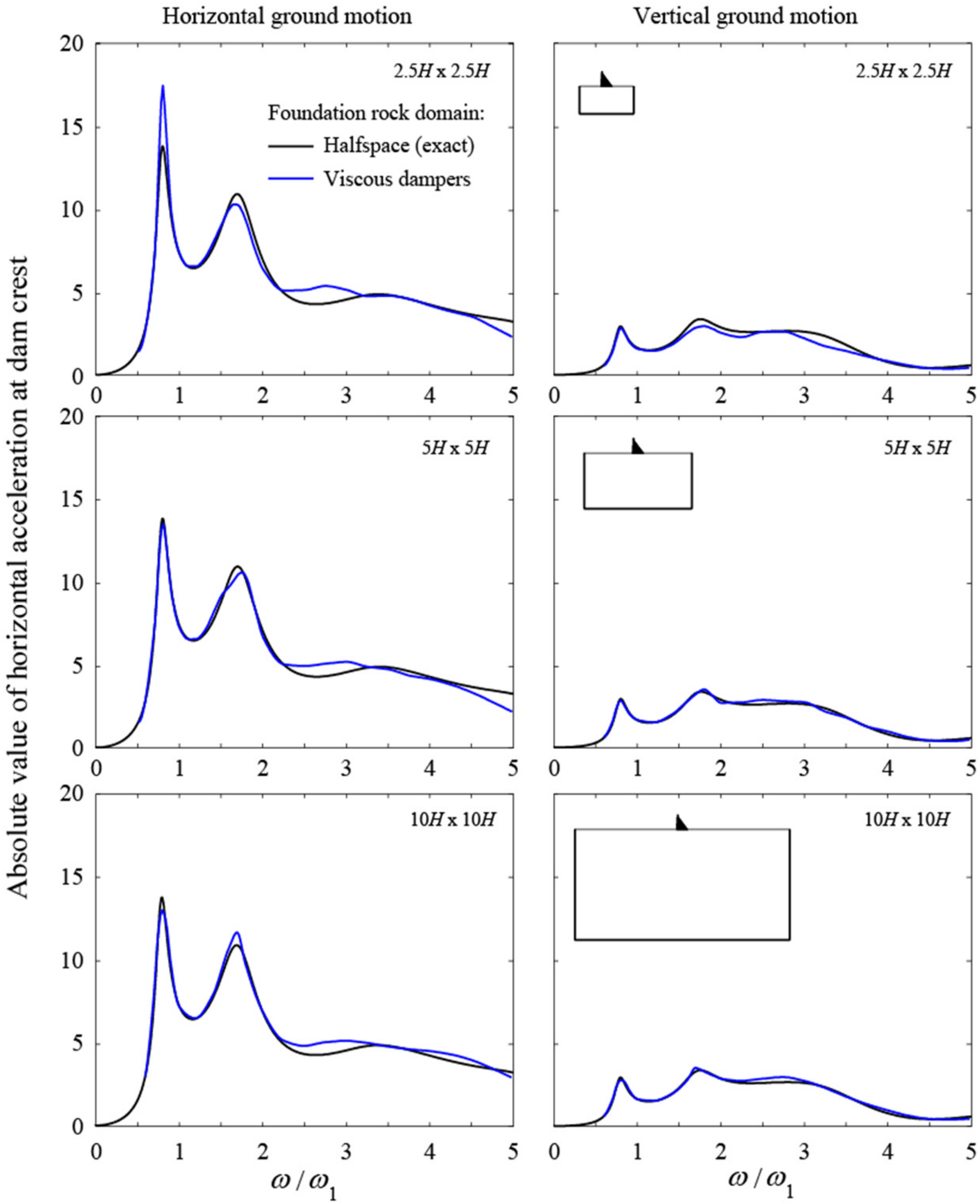
Frequency response function



- Repeat procedure at sufficient number of frequencies to get a smooth plot
- FRF is a much more stringent test than comparing response to single EQ motion

Effect of foundation-rock domain size on accuracy

Dam on flexible rock, with empty reservoir



Better accuracy for larger domains

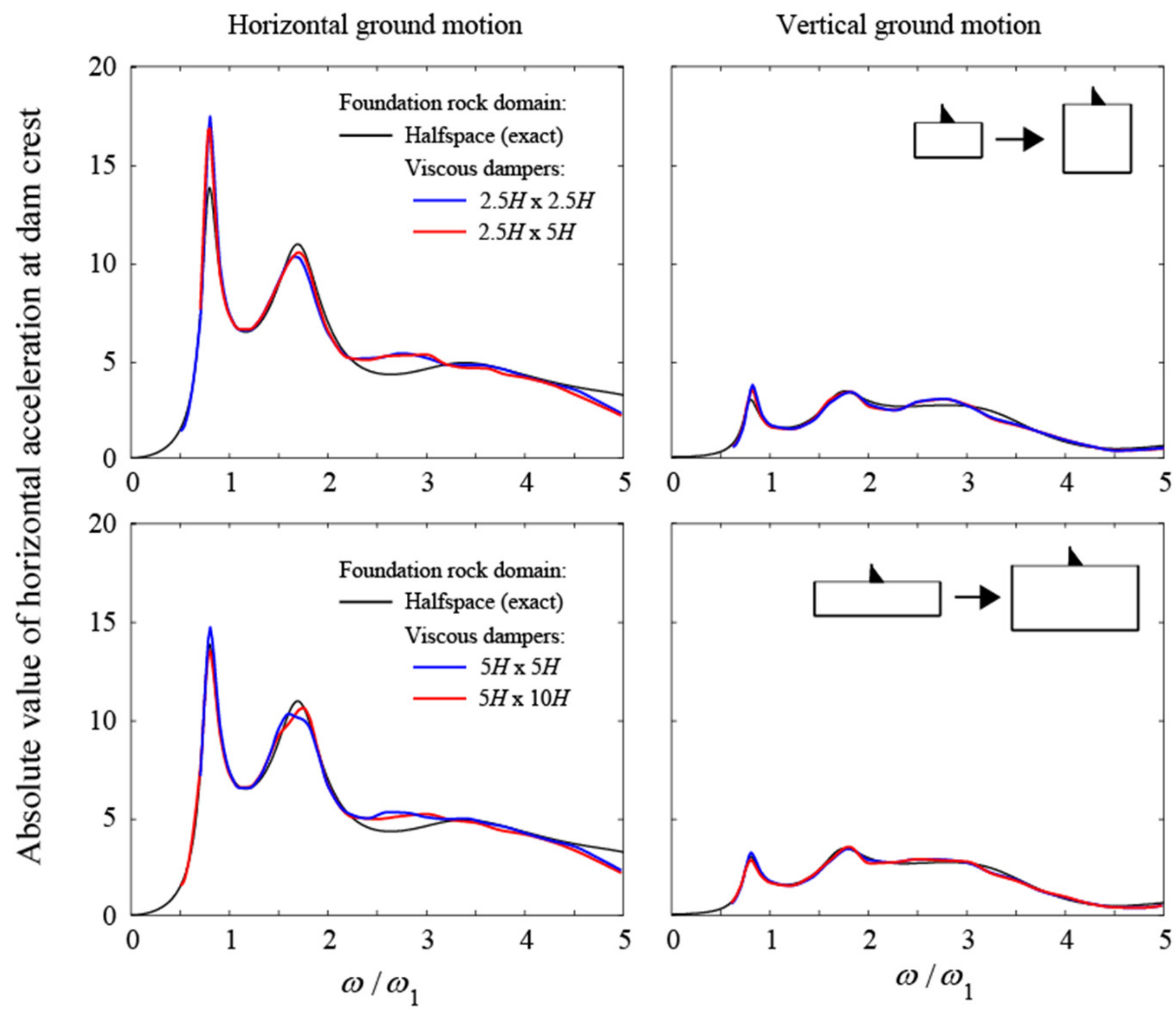
- **As expected, results improve by increasing the domain size**
- **A size of 5*H* x 5*H* seems to ensure accurate results**
- **Increasing the size beyond 5*H* seems to have little influence on the accuracy**

Effect of aspect ratio of foundation-rock domain on accuracy

Dam on flexible rock, with empty reservoir

The aspect ratio plays an important role

- **Interestingly, increasing the depth of the model does not improve accuracy**
- **This occurs because dam creates a very shallow wave field – majority of energy in horizontal directions**
- **Much better "value" to add elements in the horizontal directions!**

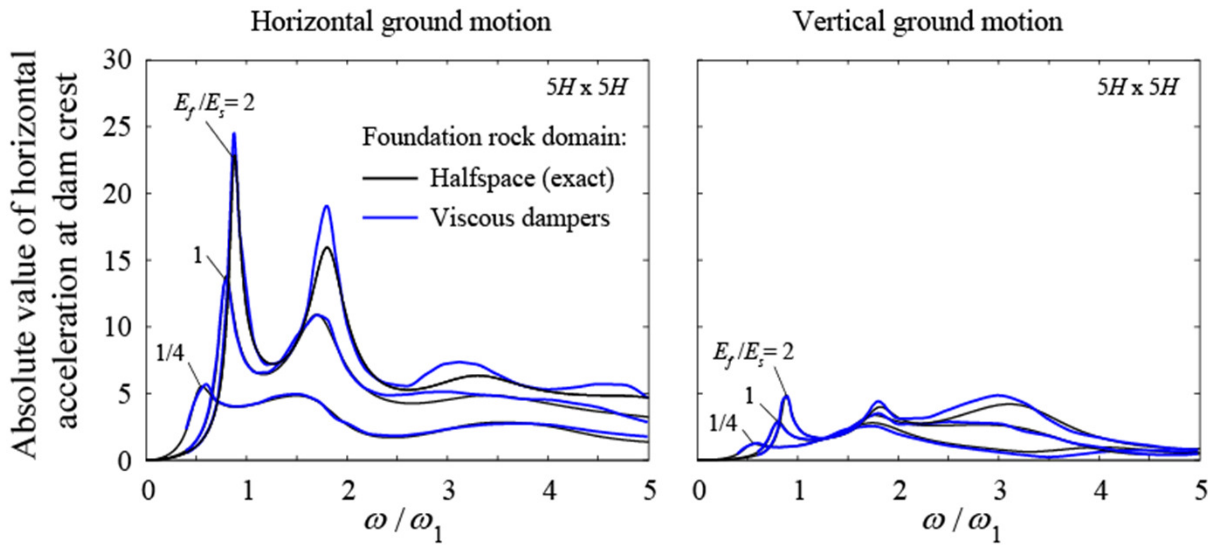


Effect of foundation-rock stiffness on accuracy

Dam on flexible rock, with empty reservoir

Softer rock tends to improve the accuracy of the results

- Counter-intuitive because interaction effects are more prominent for softer rock
- Occurs because viscous dampers performs better for waves with shorter wavelengths

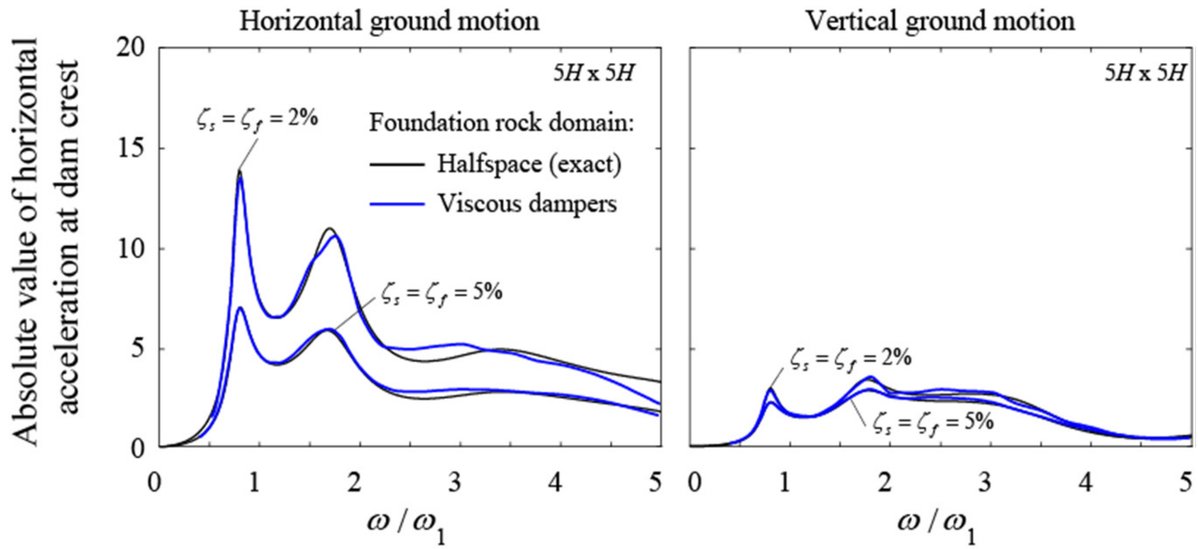


Effect of material damping on accuracy

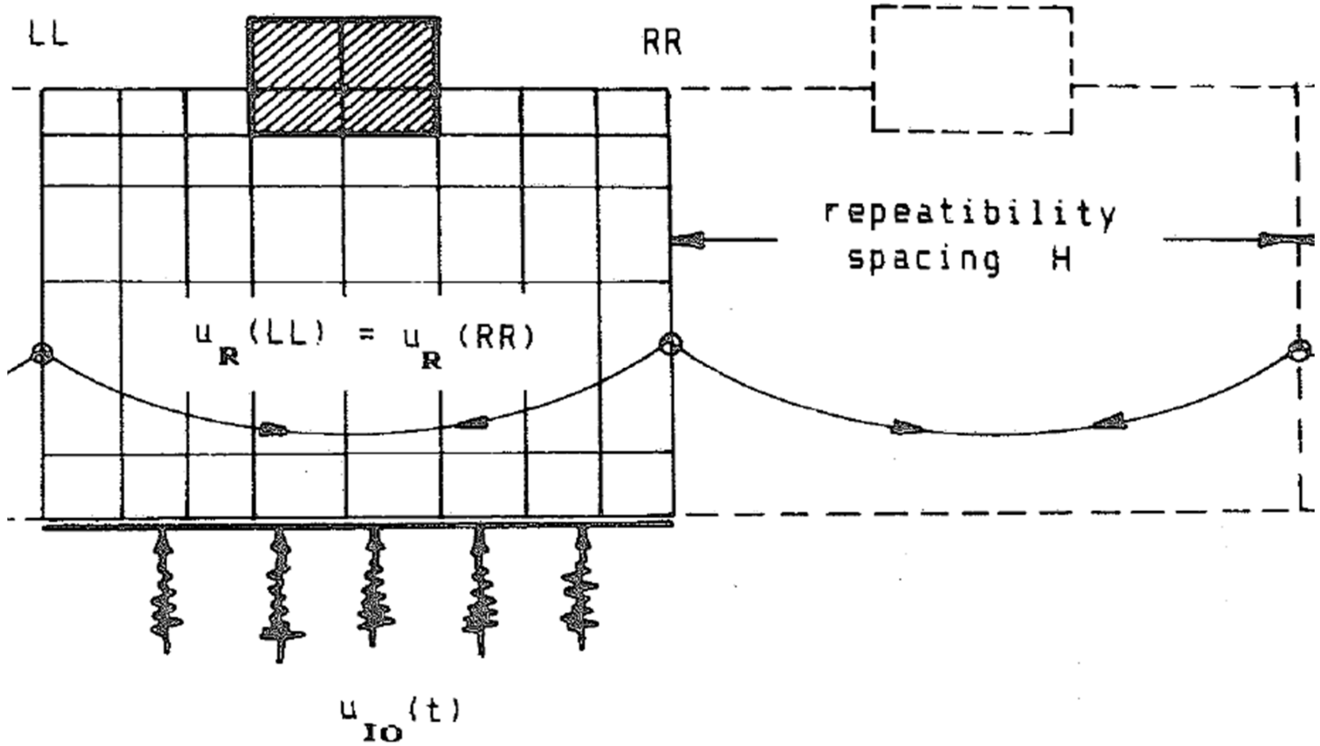
Dam on flexible rock, with empty reservoir

Increased material damping improves accuracy slightly

- As expected, results improve by increasing the amount of material damping in the rock
- More of the waves are "damped out" before reflected to the dam
- Not a very prominent effect – cannot compensate for inadequate boundary by increasing material damping



What if we ignore the absorbing boundaries altogether?



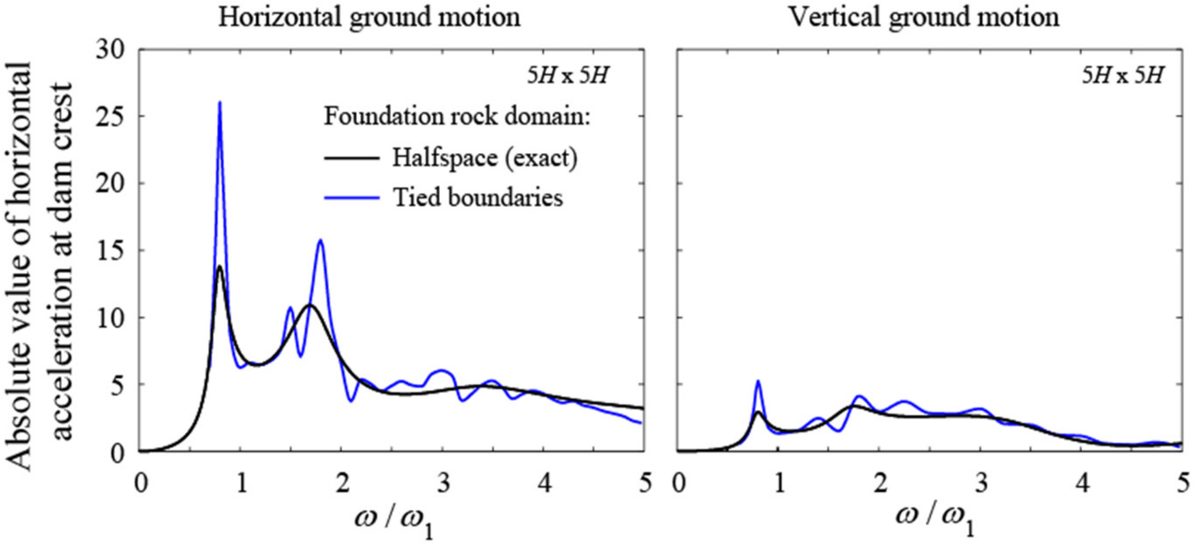
- Tied boundary model proposed by Zienkiewicz in 1989
- Popular for use in SSI analyses when modelling soft soils

What if we ignore the absorbing boundaries altogether?

Dam on flexible rock, with empty reservoir

Not an option to use tied boundaries for rock domains

- **Results are in significant error when using tied boundaries**
- **Results are poor because no energy dissipation is allowed across the side boundaries**

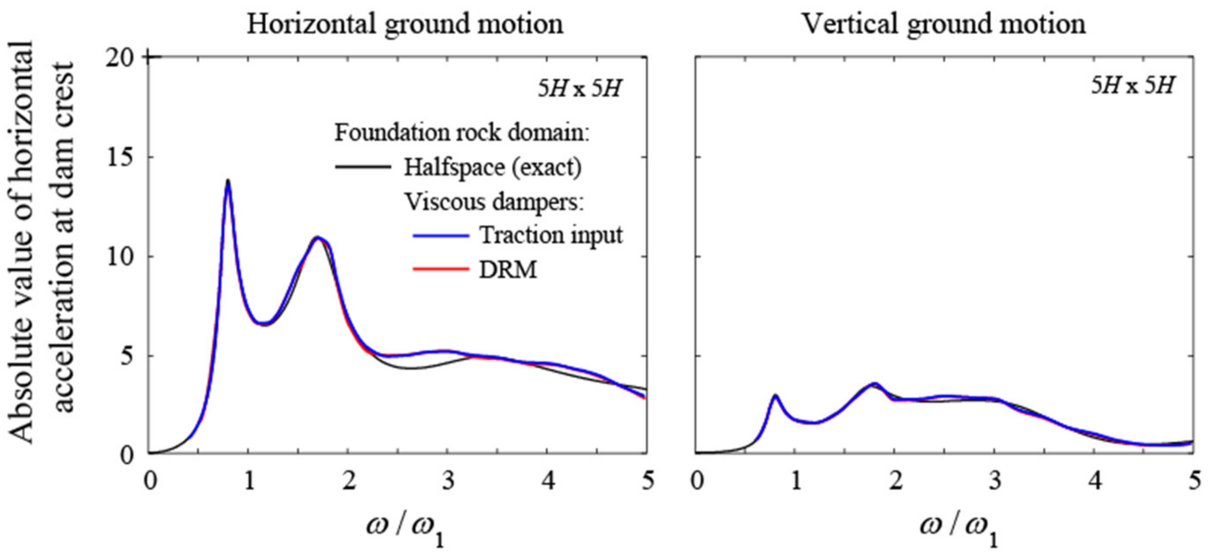


Comparing methods for applying seismic input

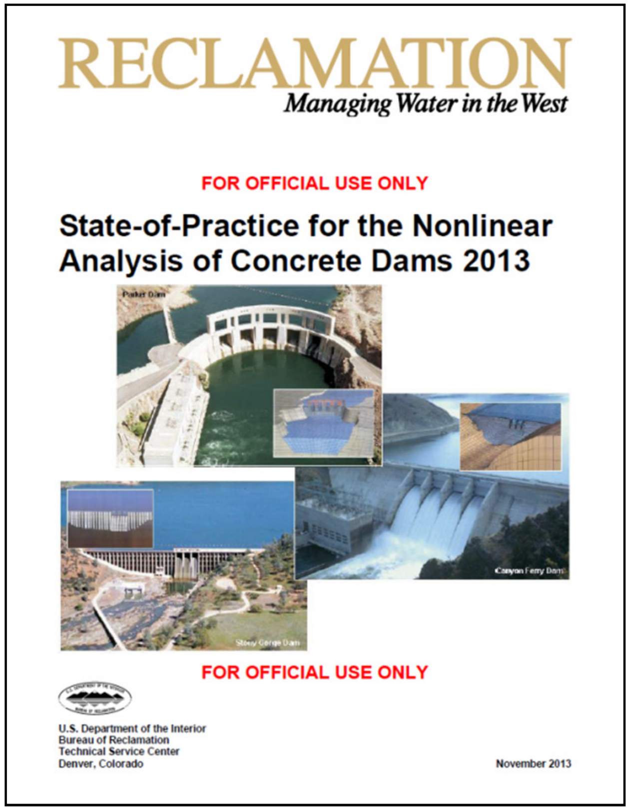
Dam on flexible rock, with empty reservoir

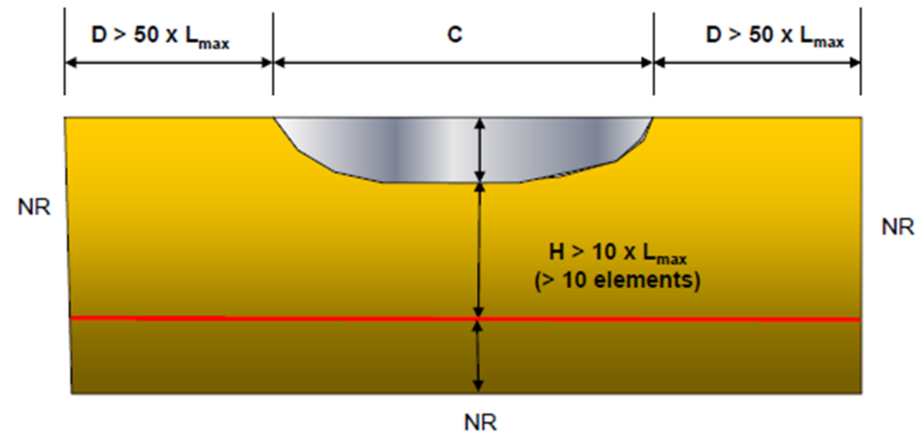
DRM and traction input give identical results

- **As expected, results are identical for the DRM and traction input method when implemented consistently**



What if we ignore forces on the side boundaries?





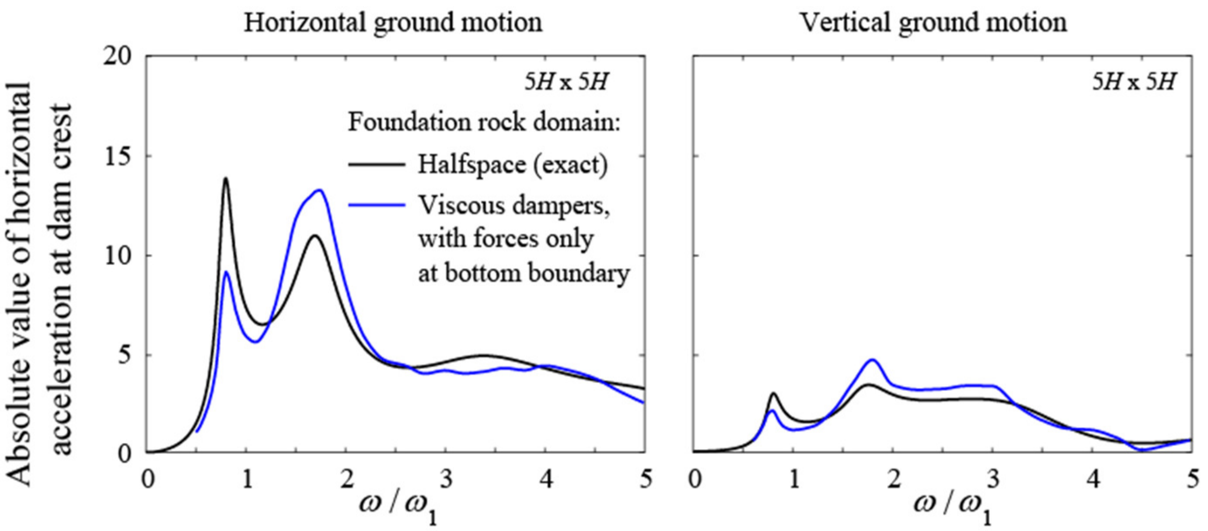
- Dam profession in the U.S. have tended to neglect forces at side boundaries
- Earthquake forces applied at single horizontal plane at depth in foundation-rock
- Model was never validated against substructure method

What if we ignore forces on the side boundaries?

Dam on flexible rock, with empty reservoir

Not an option to ignore forces on side boundaries

- Results are in significant error when ignoring forces at side boundaries
- Results are poor because side boundaries “drains” energy as the seismic waves propagates upward
- Attempts made to iterate on input motion to correct for this deficiency, but not clear that this will lead to acceptable results

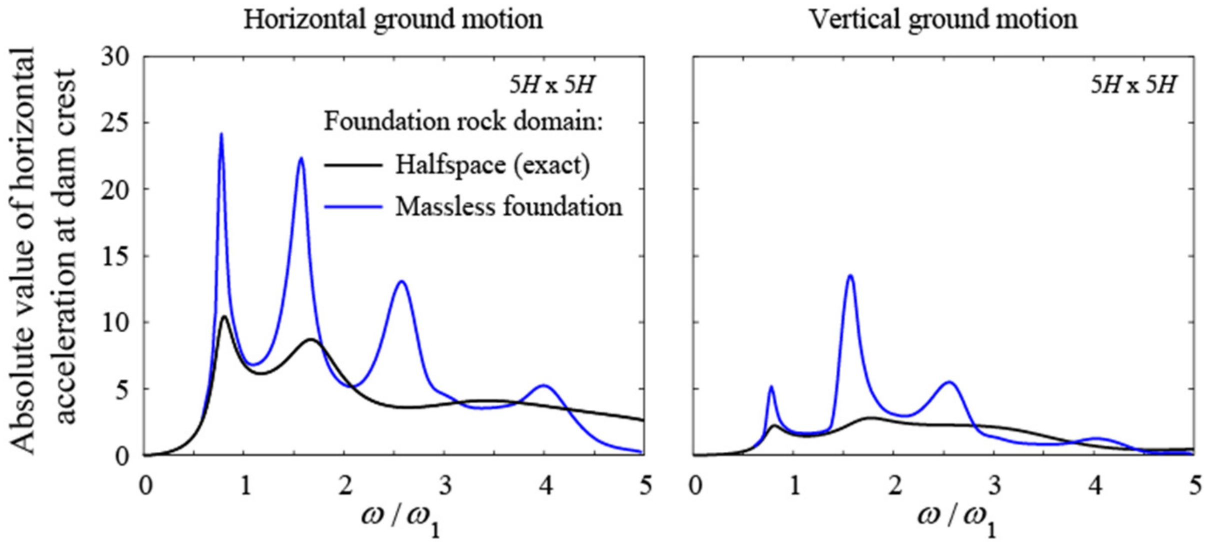


What about the massless foundation model?

Dam on flexible rock, with empty reservoir

Not an option to use the massless foundation model

- **Results are unacceptable when using massless foundation model**
- **Results are poor because of total lack of energy dissipation in the foundation rock**

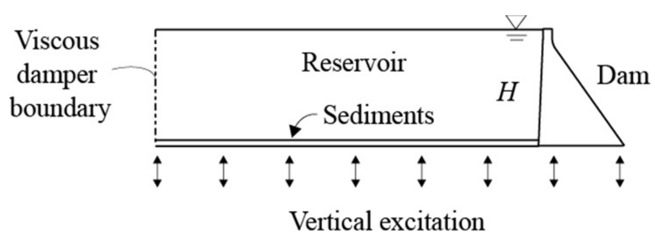


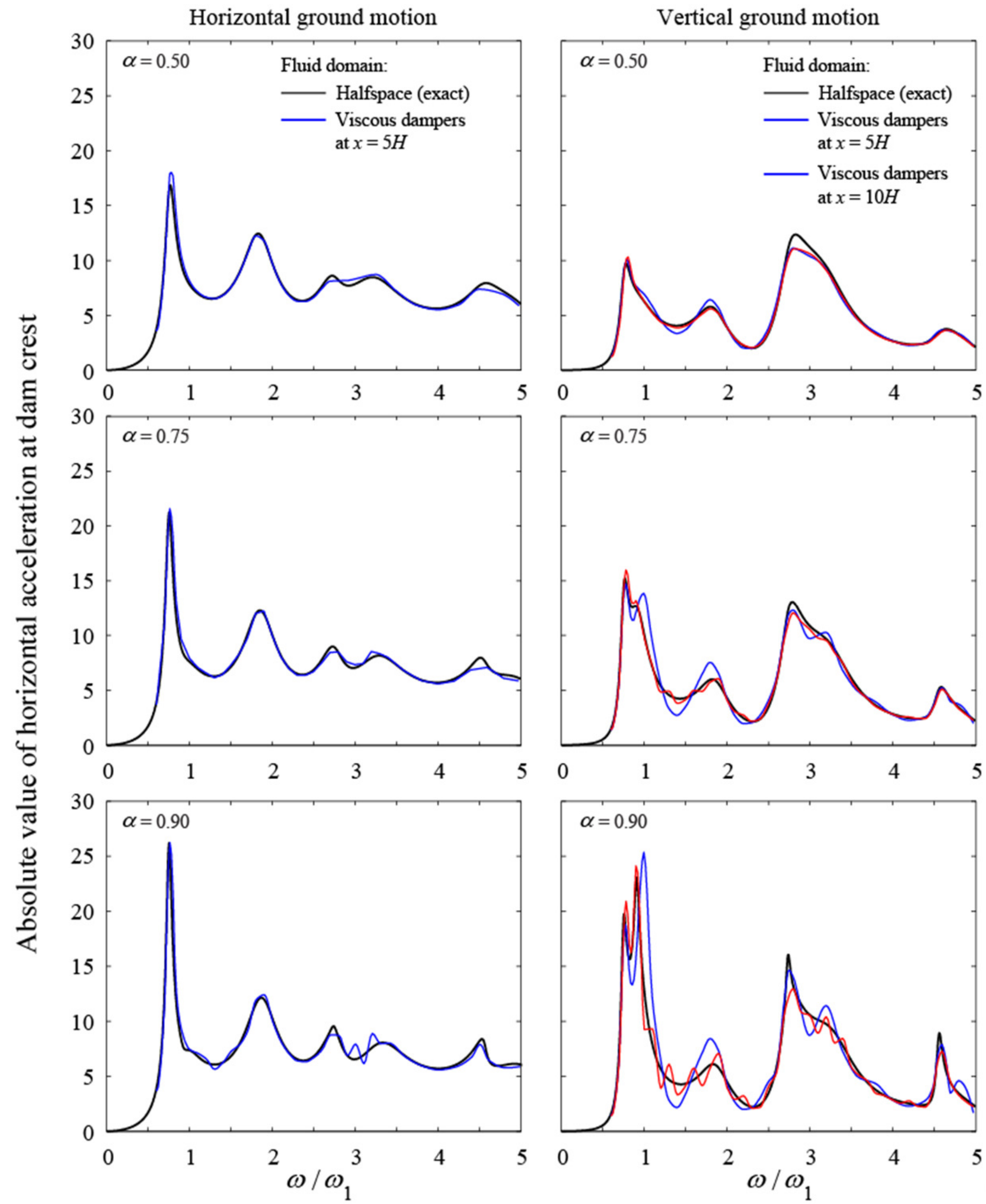
Effect of fluid domain size on accuracy

Dam on rigid rock, with full reservoir

Results are less sensitive than for foundation-rock domain

- A size of 5*H* sufficient to ensure highly accurate results for most cases
- Scatter for vertical excitation is due to unrealistic assumptions for halfspace case (uniform motion cannot extend to infinity in u/s direction)



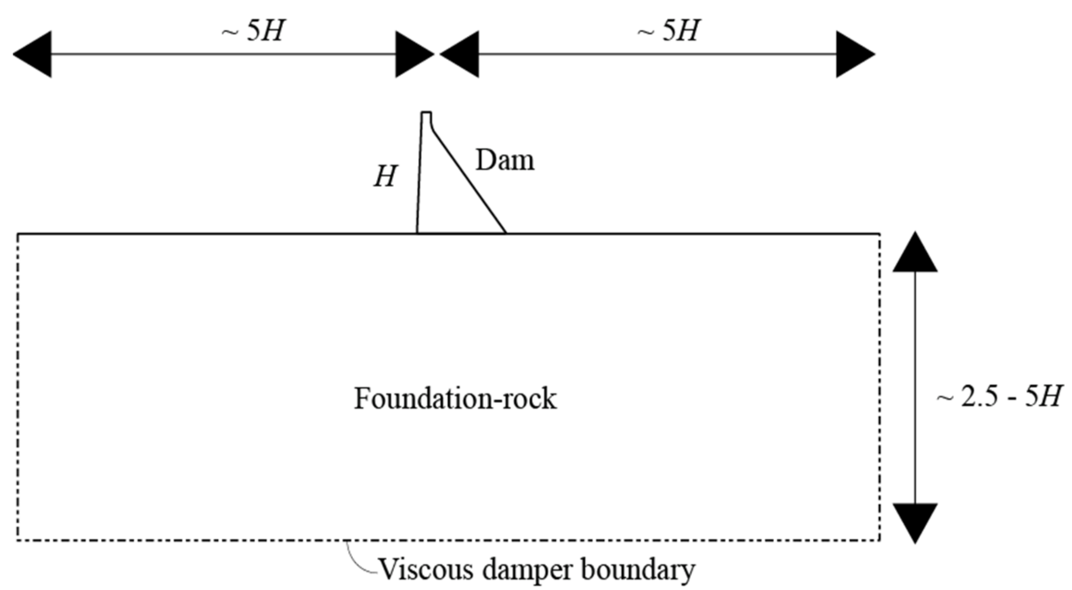


Summary and recommendations

Summary
Foundation-rock domain

Domain size of approx. 5*H* x 2.5-5*H* should ensure accurate results

- With viscous dampers, 5*H* in the horizontal and 2.5 – 5H in the vertical direction should ensure accurate results for most analysis cases
- Aspect ratio matters – adding elements in the horizontal direction offers best “value for money”
- Need sufficient mesh density to ensure propagation of high frequencies (8 – 10 elements for smallest wavelength)

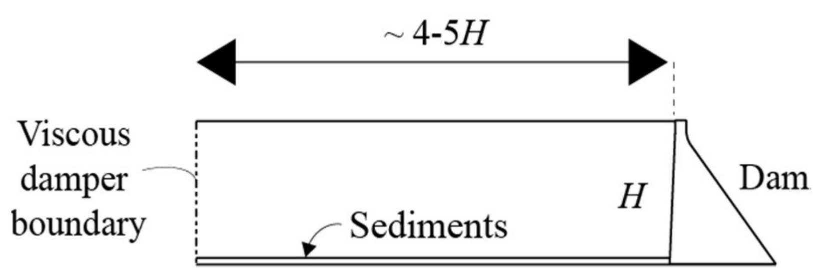


Preliminary results indicate that narrower domains can be used for 3D systems (radiation in three directions)

Summary
Fluid domain

Domain size of approx. 4-5*H* should ensure accurate results

- Response of the dam is less sensitive to the size of fluid domain
- For viscous dampers, length of 4-5*H* should ensure accurate results
- For practical analyses, the fluid domain size is most conveniently chosen as the same as the foundation-rock dimensions

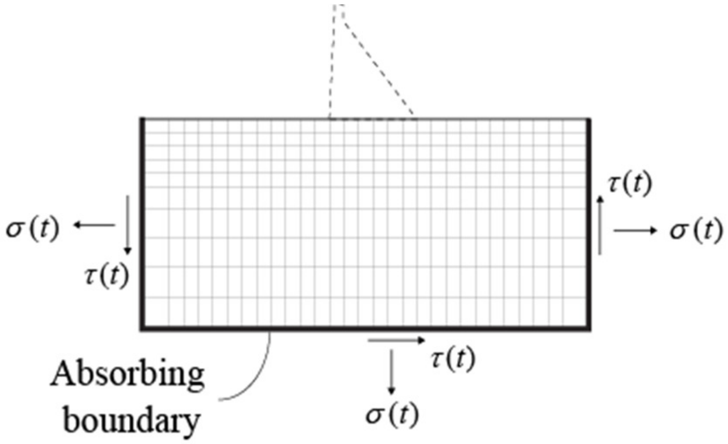


Summary

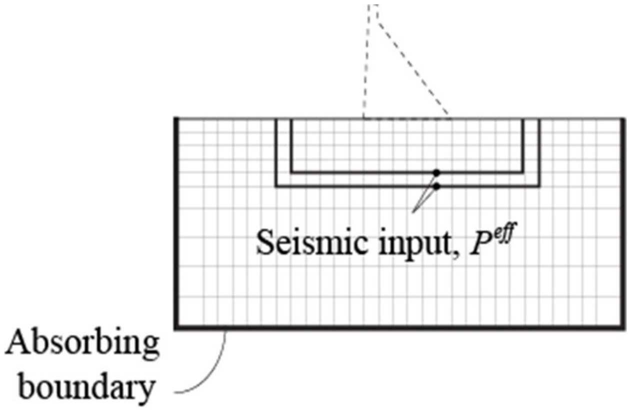
Applying the seismic input

Essential to apply the seismic input correctly

- Starting with a surface recorded free-field motion, two methods can be used to apply effective earthquake forces
  - Traction input method
  - Domain Reduction Methods (DRM)
- Should avoid using models with clearly demonstrated deficiencies (e.g. massless rock, or neglecting forces on side boundaries)



Traction input



DRM

How can this be implemented for practical analyses?

Unbounded domains

Foundation rock domain

- Standard solid elements for rock
- Absorbing boundaries (such as viscous dampers) at truncations

Fluid domain

- Acoustic elements are standard in most FE codes
- Absorbing boundaries (such as viscous dampers) at truncation
- Can use simple line elements to model reservoir bottom absorption

Method for seismic input

Automatic treatment inside FE code

- An increasing number of FE codes have “free-field” elements available (e.g. FLAC, Plaxis, Code_Aster, ++)
- DRM formulation less available (LS-DYNA)

Alternatively forces can be computed and applied to model independently of FE code

- However, this requires a bit of “book-keeping”, especially for 3D systems
- I’m currently developing a set of Matlab scripts to perform such tasks for an arbitrary 3D dam-water-foundation rock system

Thank you for your attention!

Arnkjell Løkke
Department of Structural Engineering
NTNU

Contact:
E-mail: *arnkjell.lokke@ntnu.no*
Phone: *+47 48 04 88 43*