Earthquake analysis of concrete dams as a wave propagation problem

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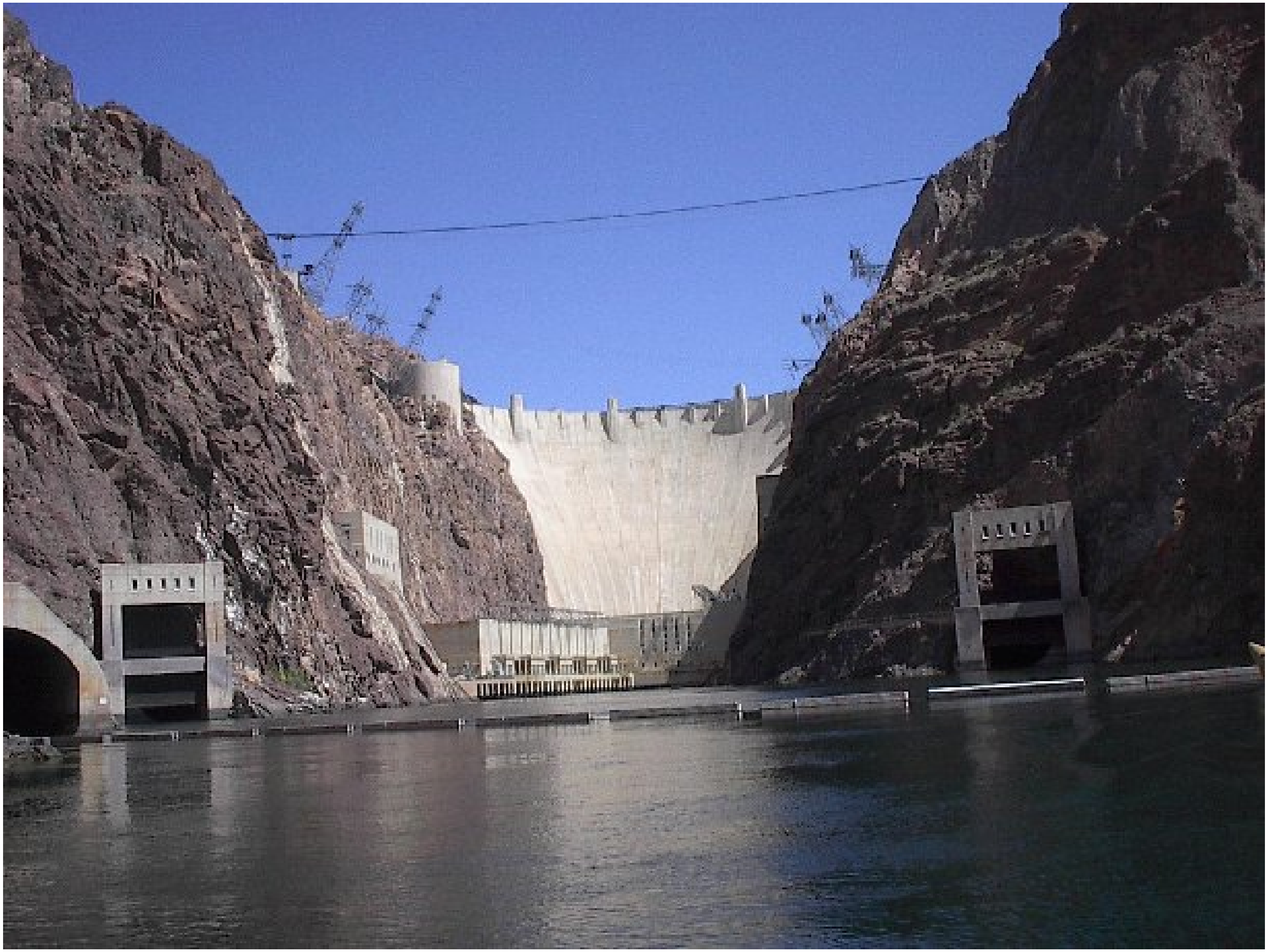
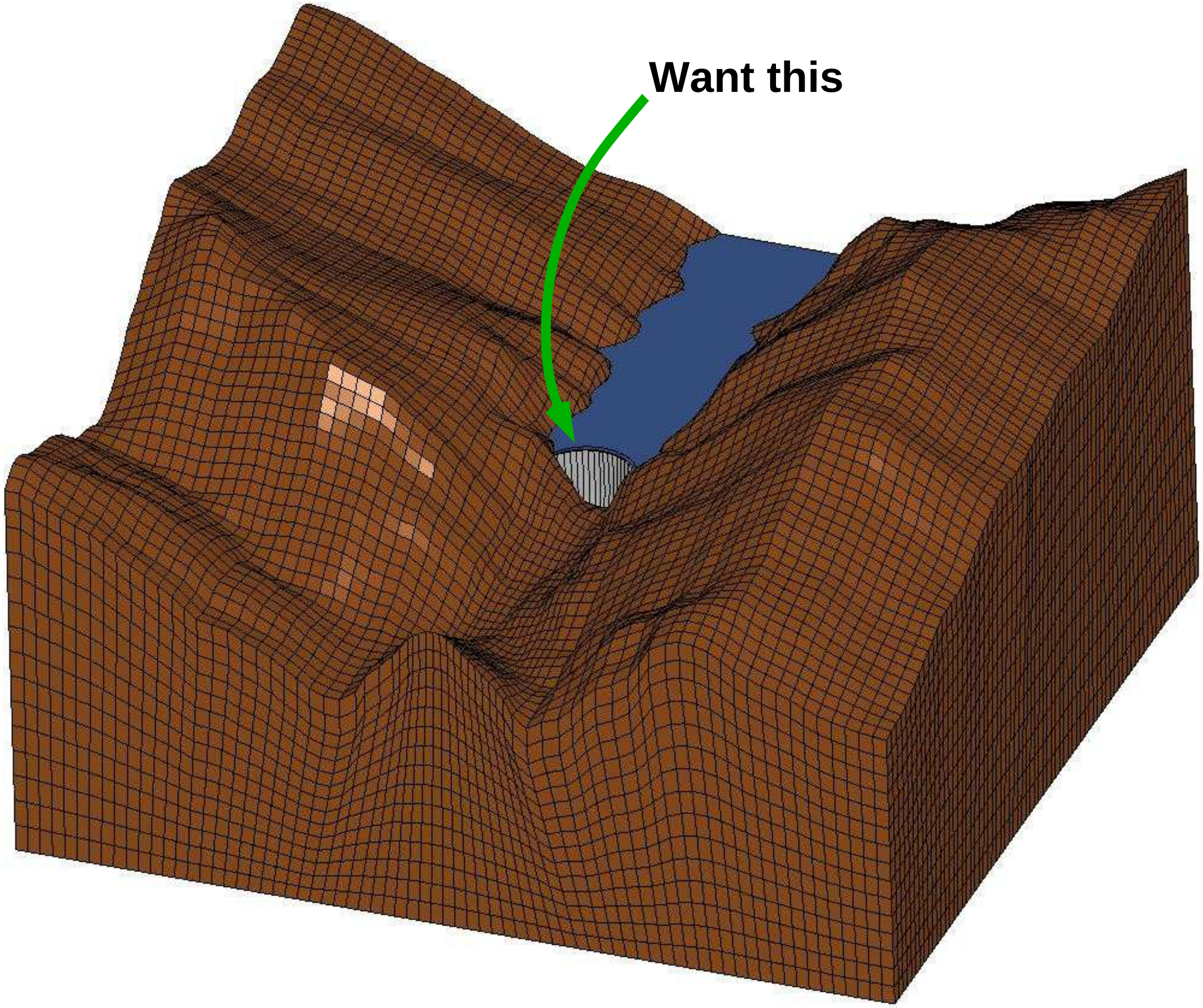
University of California, Berkeley

Introduction

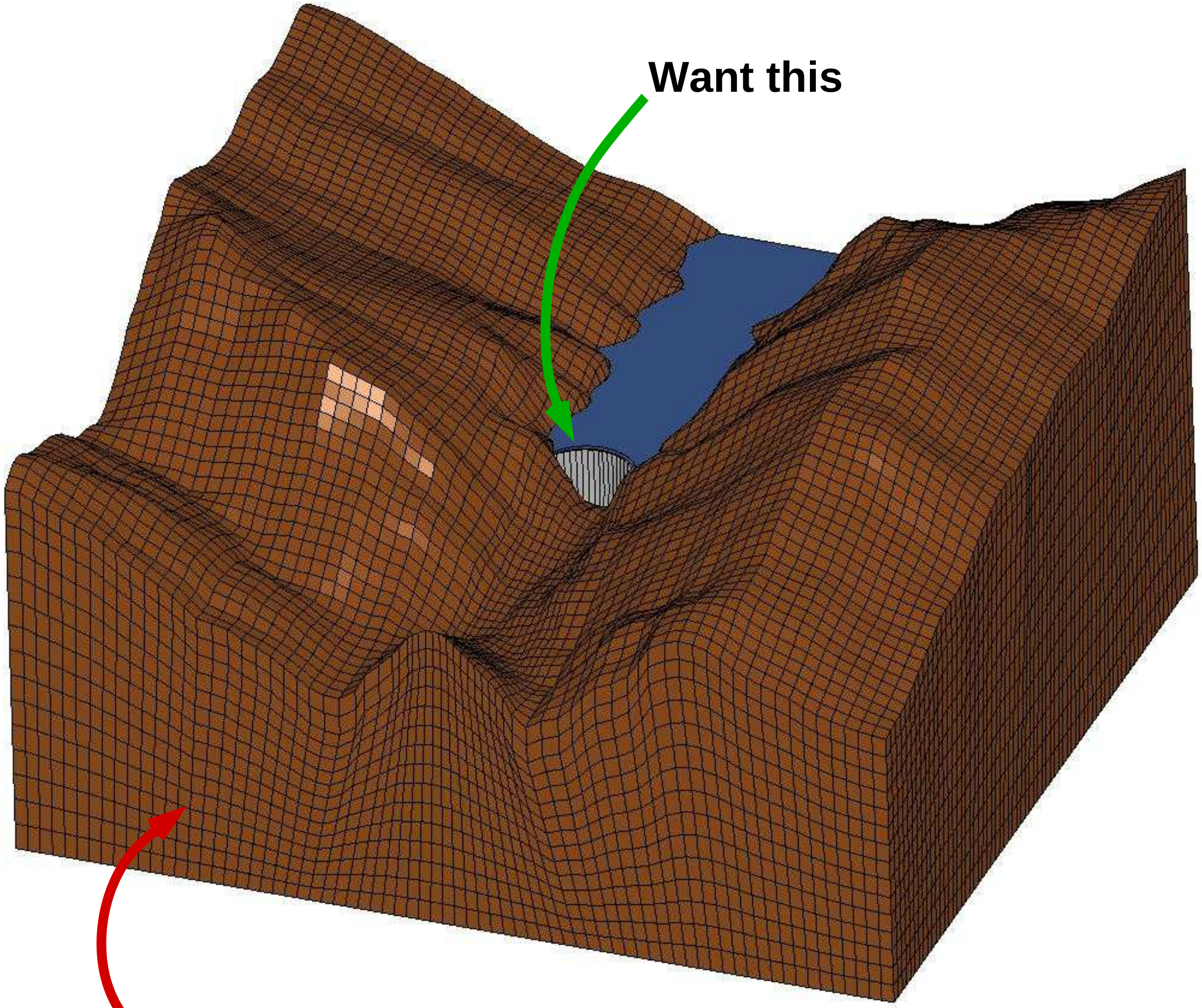


Morrow Point dam

Morrow Point dam



Morrow Point dam



Introduction

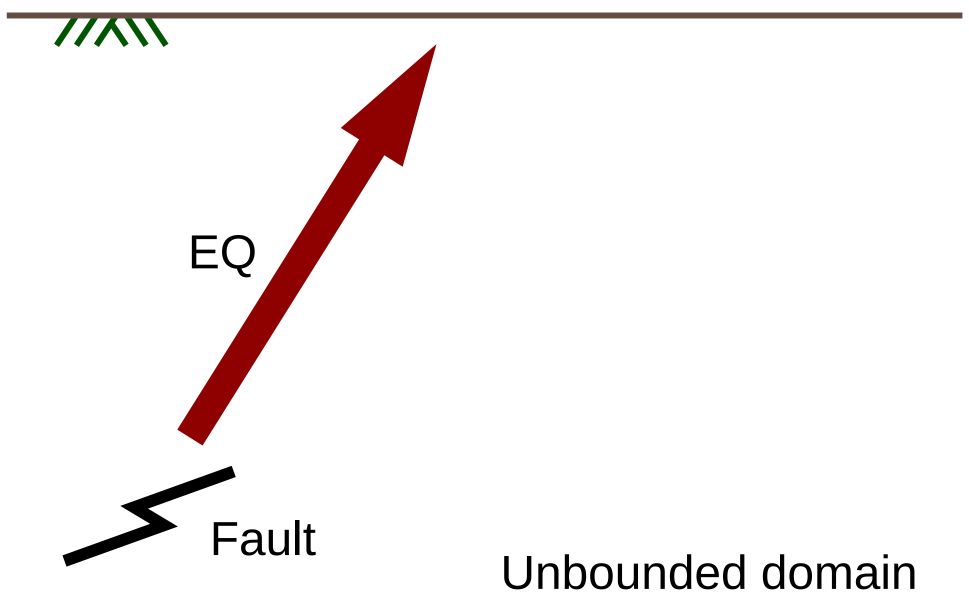
State-of-the-art practice

We need a large foundation domain in order to:

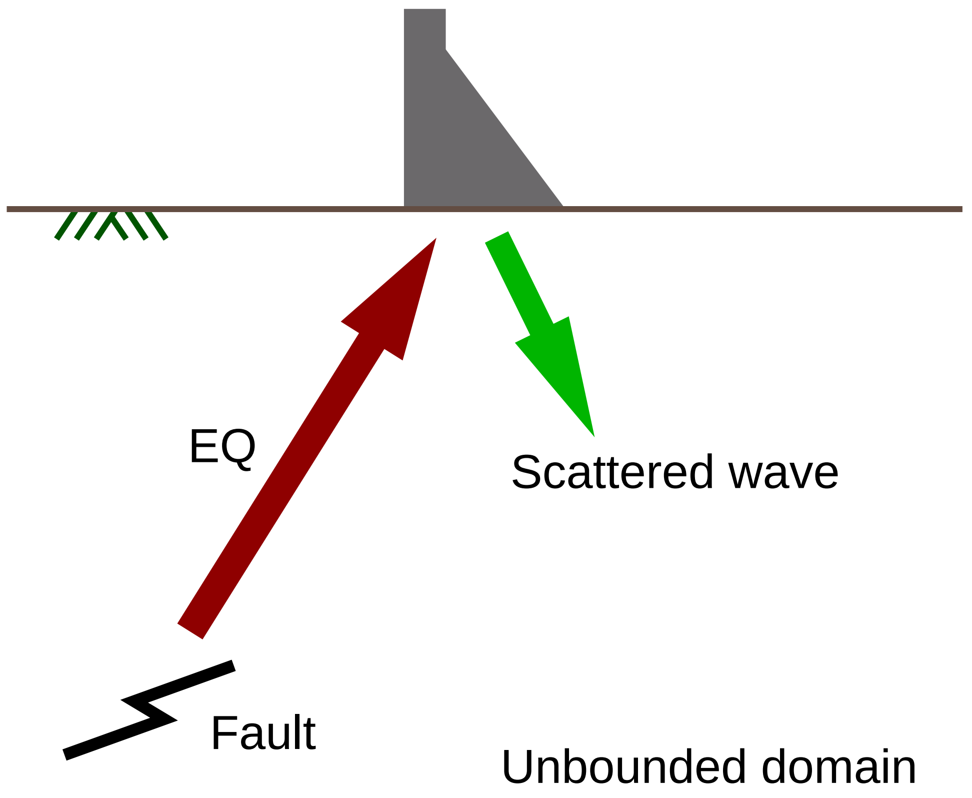
1. accurately model the unbounded foundation
2. apply ground motions forces at depth (deconvolution)

How do we avoid the large foundation model?

Earthquake free field

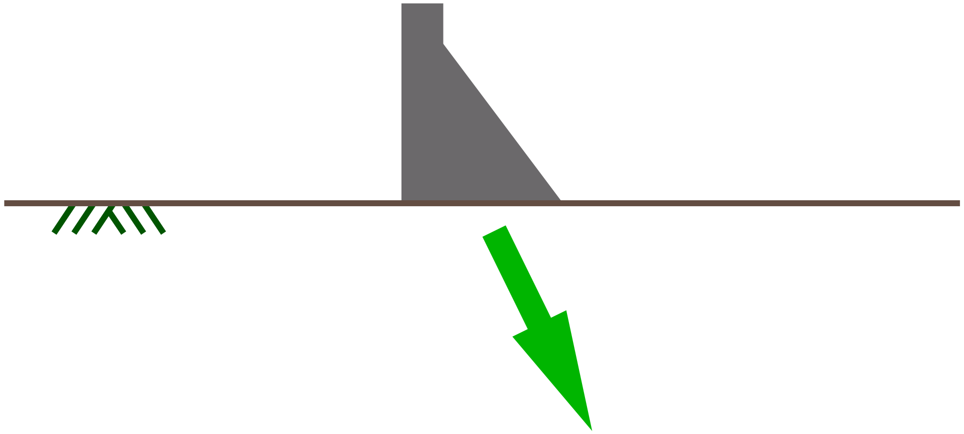


Dam in earthquake



Dam interacts with and scatters earthquake motion

Scattered wave field

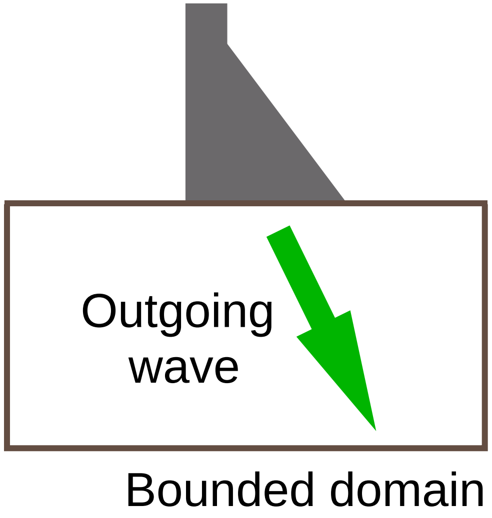


Scattered wave
(outgoing)

Unbounded domain

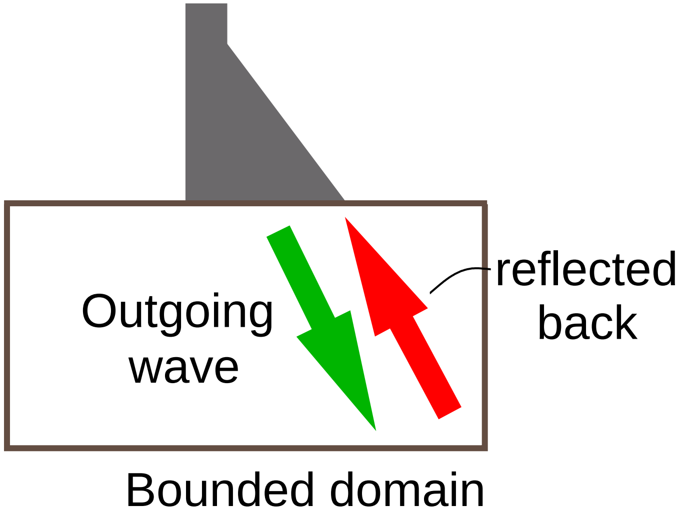
Subtract free-field motion to eliminate EQ source

Bounded-domain approximation



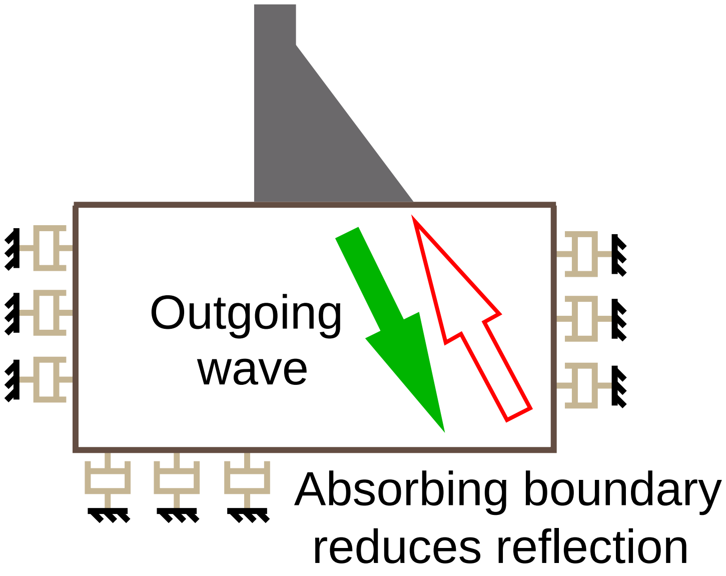
Cannot model unbounded domain

Bounded-domain approximation



Cannot tolerate large reflections

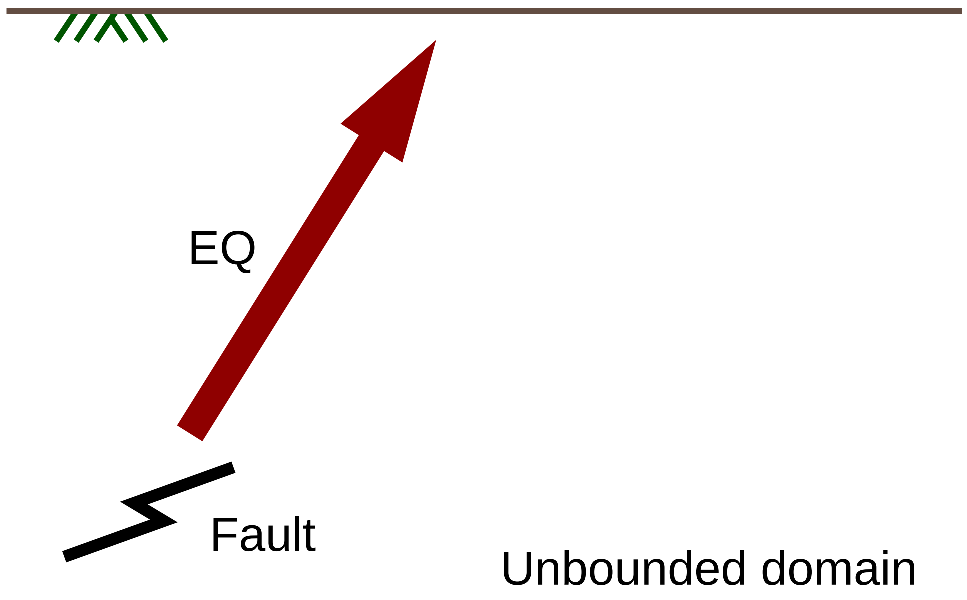
Dam on bounded foundation with absorbing boundary



Absorbing boundary simulates unbounded foundation

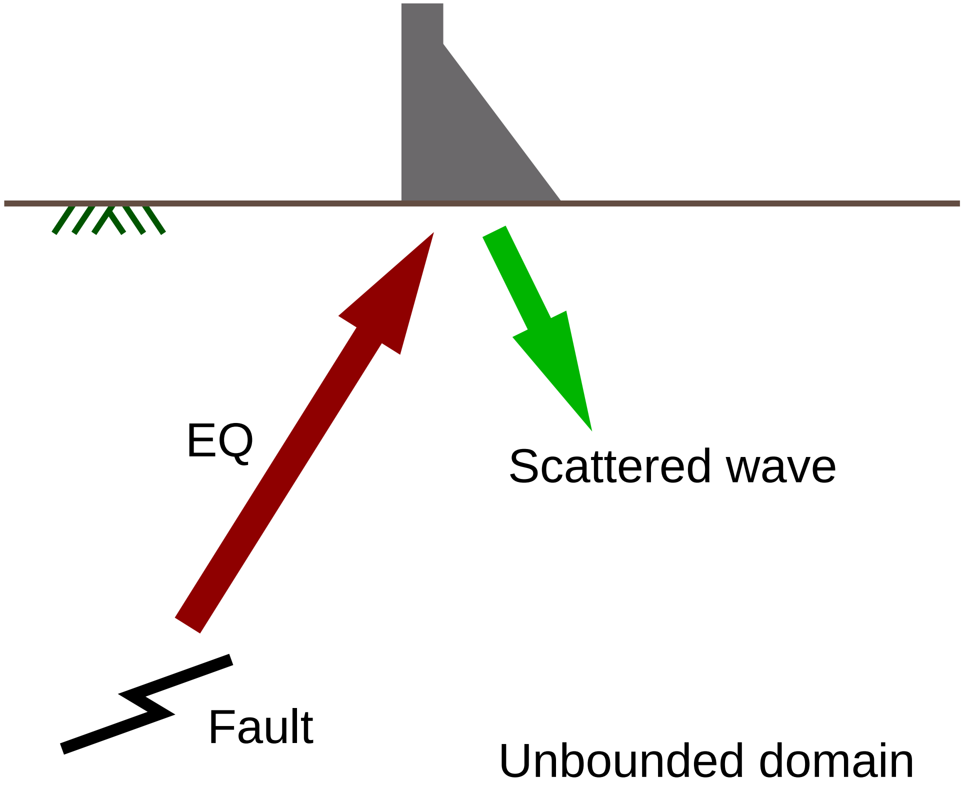
REVIEW

Step 1: Get free-field ground motions



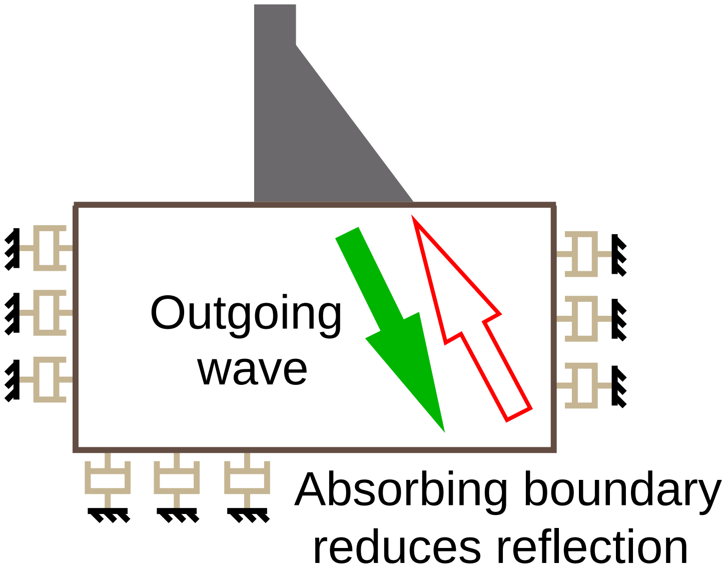
Earthquake generates free-field ground motions

Step 2: Model dam-rock interaction



Dam interacts with and scatters earthquake motion

Step 3: Absorb outgoing scattered waves



Absorbing boundary for outgoing waves

Review of earthquake analysis

All together

Step 1: Get free-field ground motions

Step 2: Model dam-rock interaction

Step 3: Absorb outgoing scattered waves

☛ Three fundamental problems in numerical simulation of wave propagation:

Problem 1: Propagate waves accurately

Problem 2: Analyse wave scattering effects

Problem 3: Model unbounded domains

Review of earthquake analysis

All together

Step 1: Get free-field ground motions [later]

Step 2: Model dam-rock interaction ✓

Step 3: Absorb outgoing scattered waves ✓

☛ Three fundamental problems in numerical simulation of wave propagation:

Problem 1: Propagate waves accurately

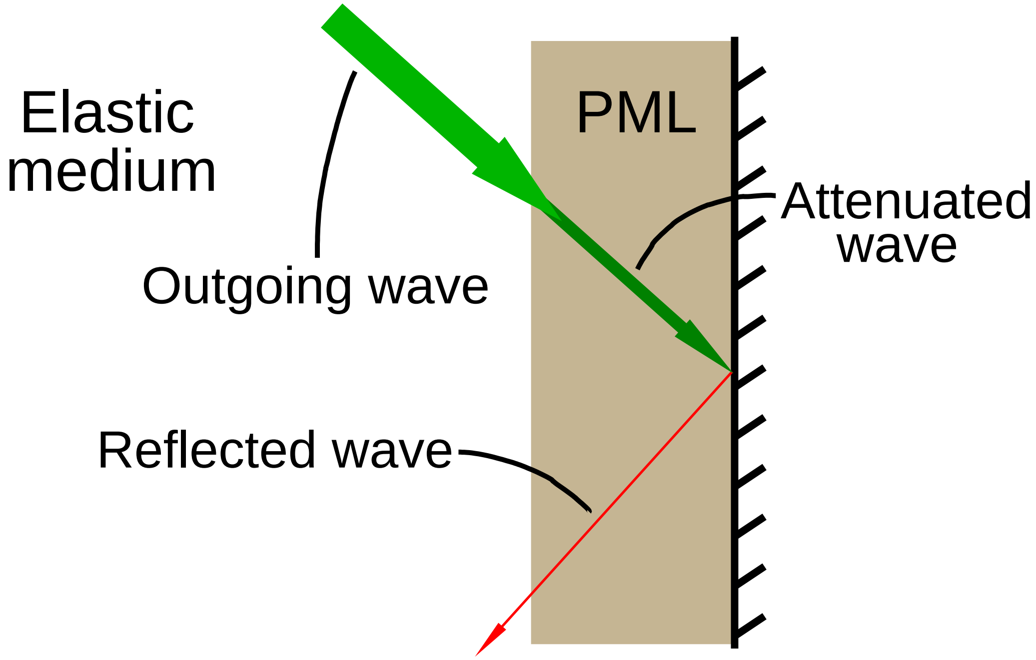
Problem 2: Analyse wave scattering effects

Problem 3: Model unbounded domains

PML absorbing boundary

Choice of absorbing boundary

Practical choice: perfectly matched layer (PML)



No reflection from interface ⇒ perfectly matched

Reflected wave can be made insignificant

PML absorbing boundary

Perfectly matched layer (PML)

Originally developed for electromagnetic waves

[Bérenger (1994); Chew-Weedon (1994)]

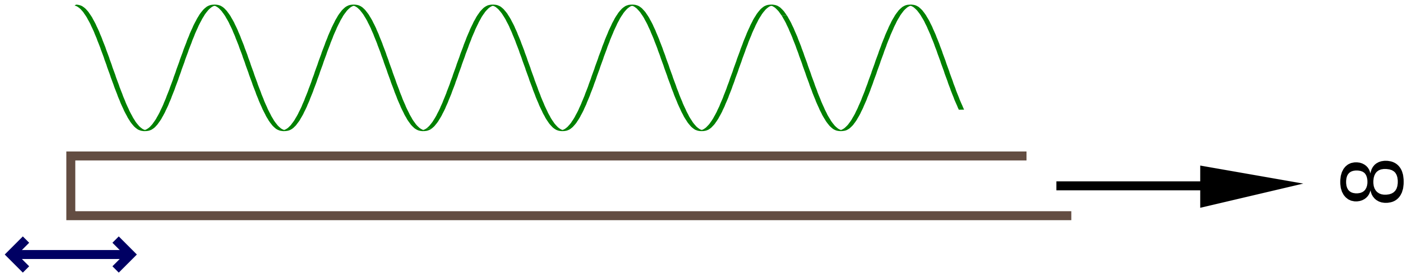
Later developed for elastic waves with

- displacement-based FE implementation
- explicit time-integration

[Basu-Chopra (2003,2004), Basu (2009)]

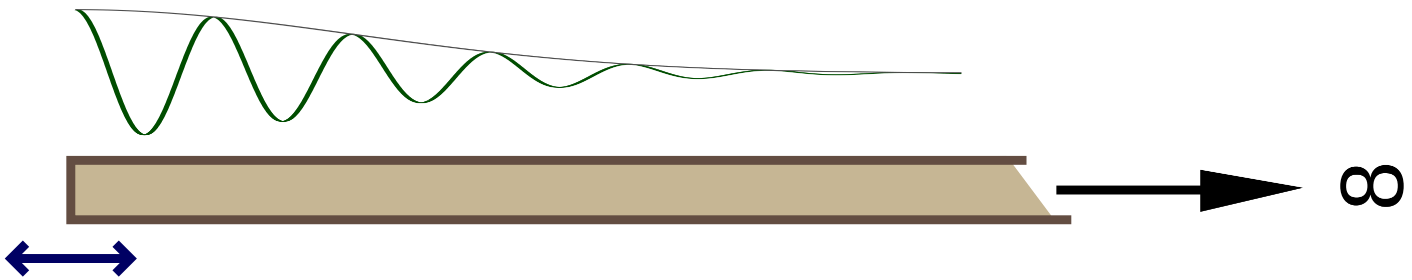
Elastic rod: a one-dimensional system

Semi-infinite rod: simple model of unbounded half-space



Elastic rod: a one-dimensional system

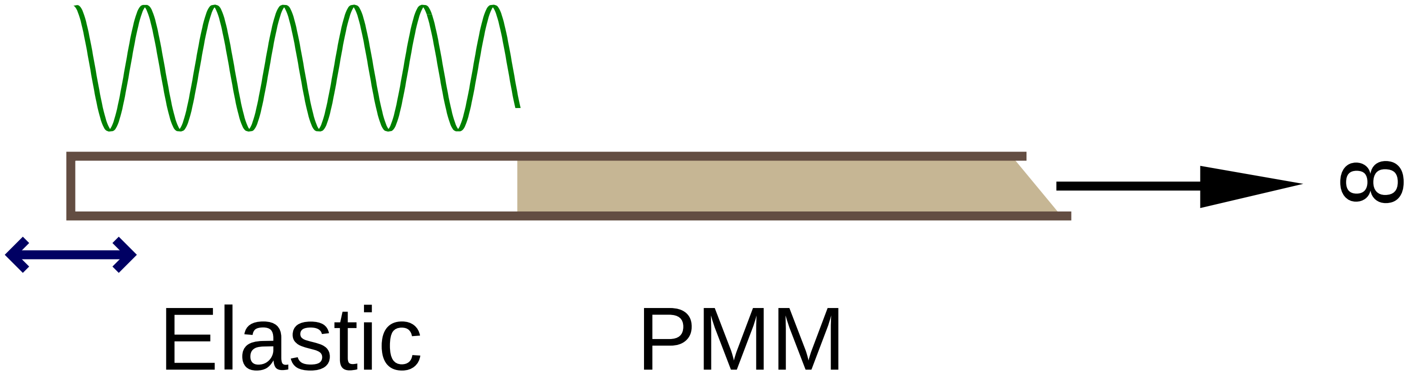
Perfectly matched medium using coordinate stretching



Coordinate stretching gives attenuated wave solutions

PML: elastic rod

Elastic rod with PMM

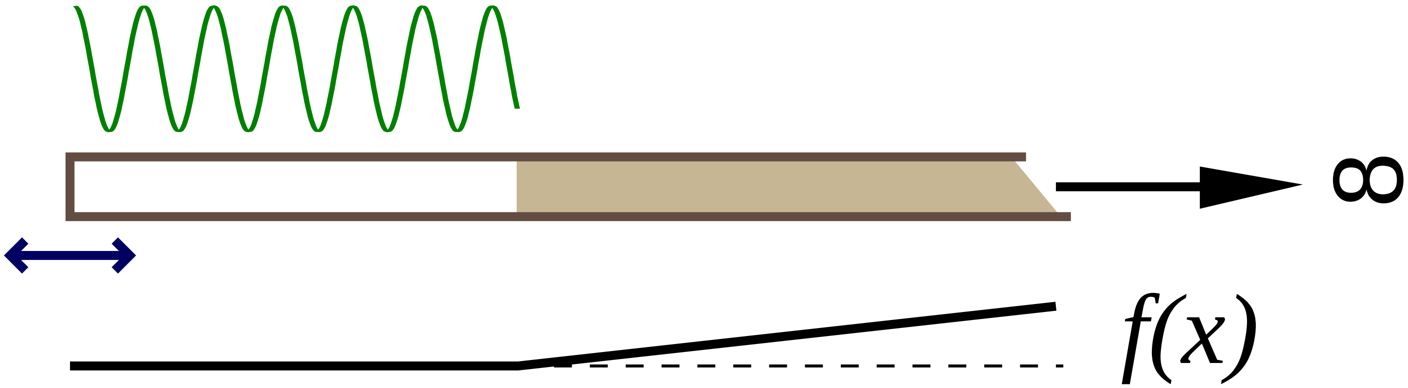


Reflection at interface?

No, elastic medium is a PMM with damping $f(x) \equiv 0$

PML: elastic rod

Elastic rod with PMM



Reflection at interface?

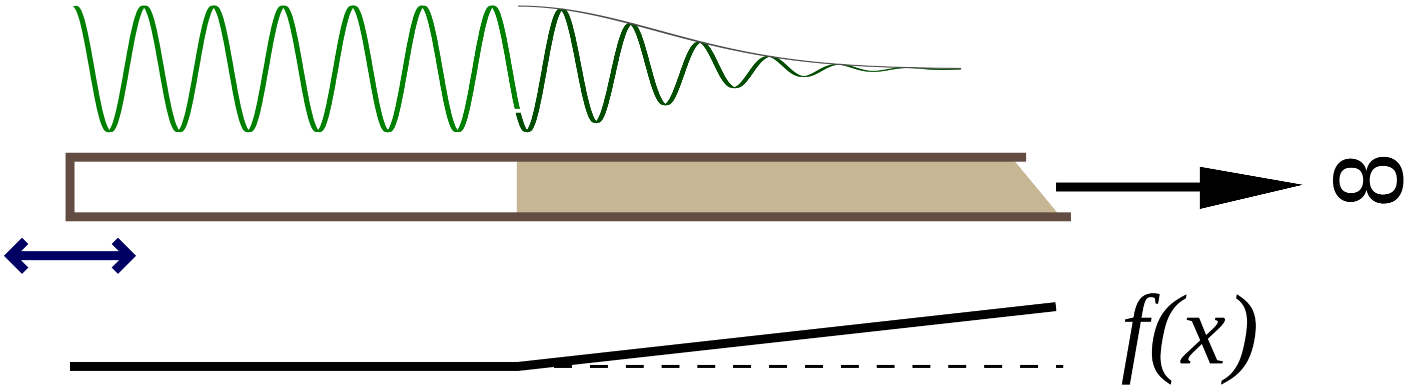
No, elastic medium is a PMM with damping $f(x) \equiv 0$

Perfect matching property

$f(x)$ continuous across interface

$\Rightarrow$ Elastic medium $+$ PMM $=$ one PMM $\Rightarrow$ No interface!

Elastic rod with PMM

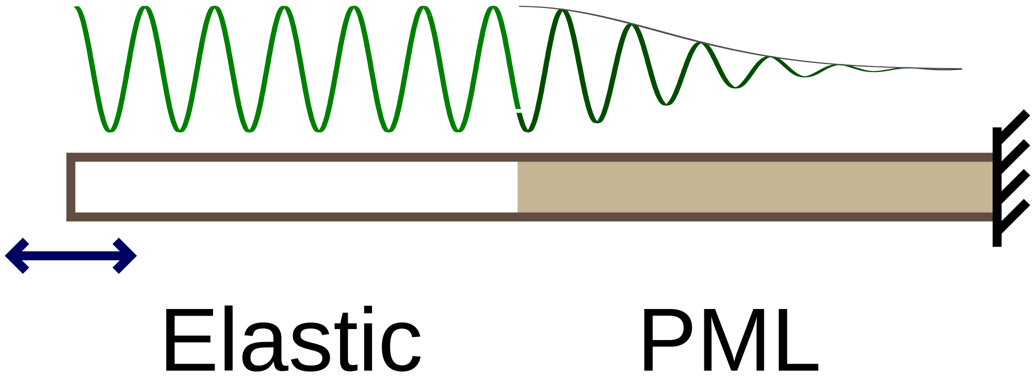


Wave is absorbed and attenuated in the PMM

Now, get rid of unbounded domain:

☛ truncate after wave is sufficiently attenuated

Elastic rod with PML

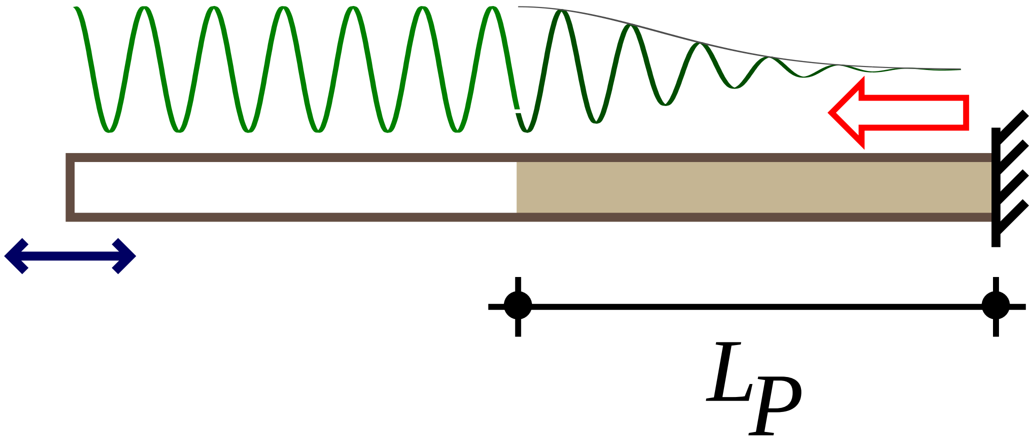


Truncate to get the perfectly matched layer

Effect of truncation?

PML: elastic rod

Elastic rod with PML



Truncate to get the perfectly matched layer

Effect of truncation? Wave is reflected

- Reflected wave amplitude controllable by f and L_P

Simple choices of f give excellent results

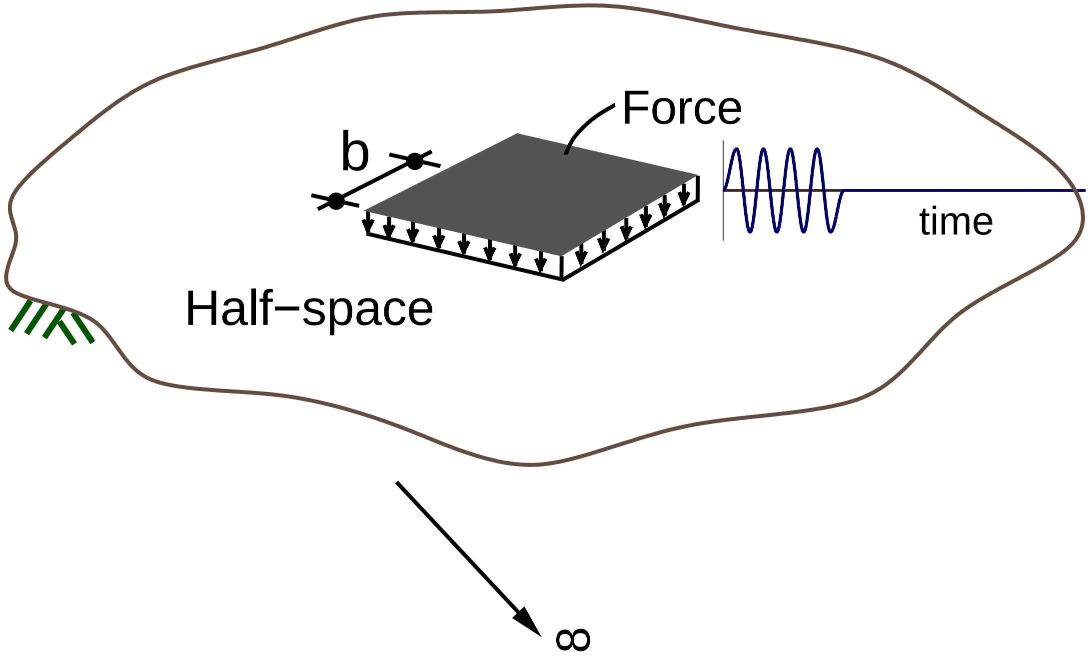
PML: elastic waves

Salient features of PML

1. Extends to 2D and 3D, time and frequency domain
2. PML applicable to any linear material
3. Attenuated P- and S-waves, Rayleigh waves &c. through coordinate-stretching, not material damping
4. No reflection from interface. PML absorbs waves of
   - all frequencies
   - all angles of incidence
5. Reflection from outer boundary can be controlled by attenuation function and depth of layer.

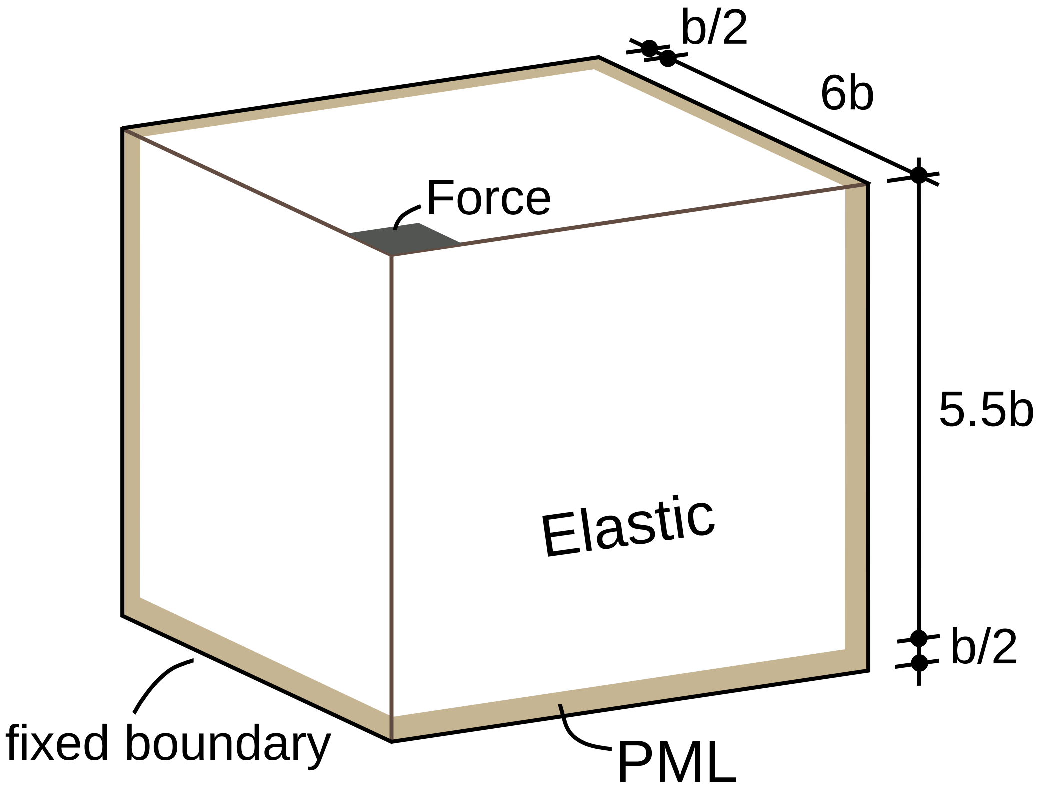
PML: 3D example

Applied vertical force over square area on a half-space



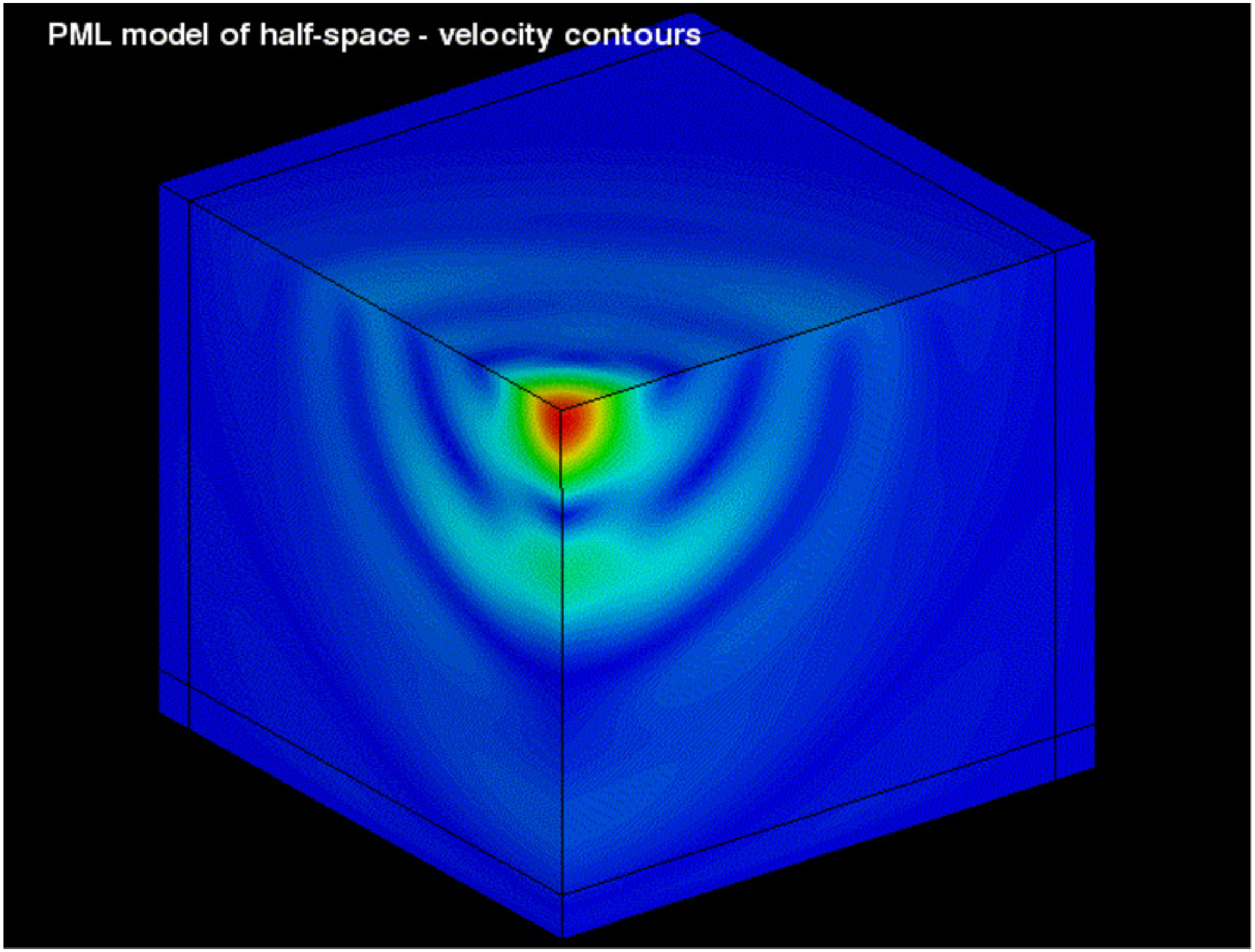
PML: 3D example

PML model (quarter mesh)



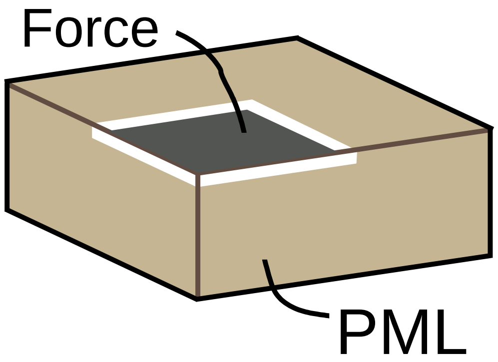
≈12 elements per shortest wavelength; 5-element PML (mesh density in PML same as in elastic medium)

PML: 3D example



PML: 3D example

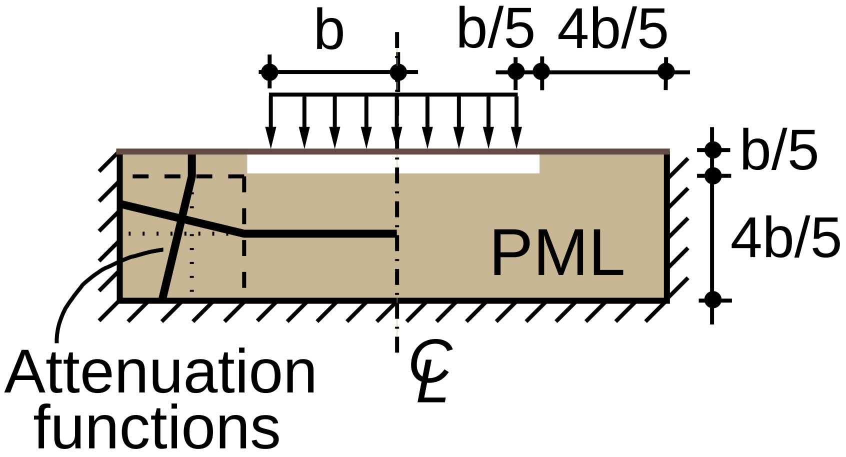
Reduce the domain size



Maintain mesh density

PML: 3D example

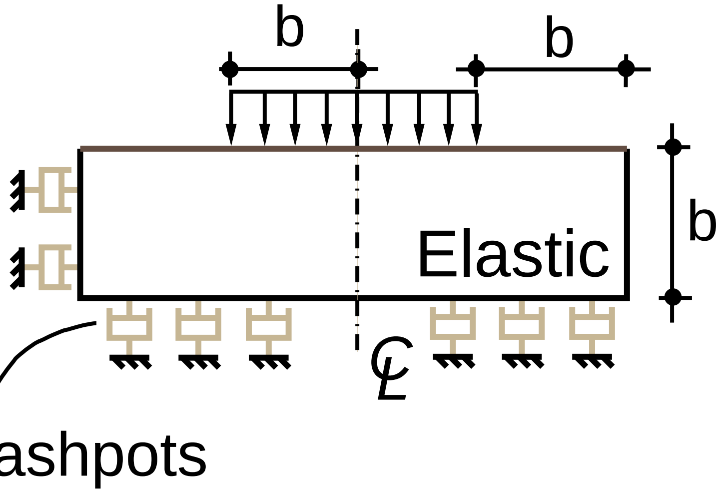
PML model (cross-section)



PML placed very close to source (8-element PML)

PML: 3D example

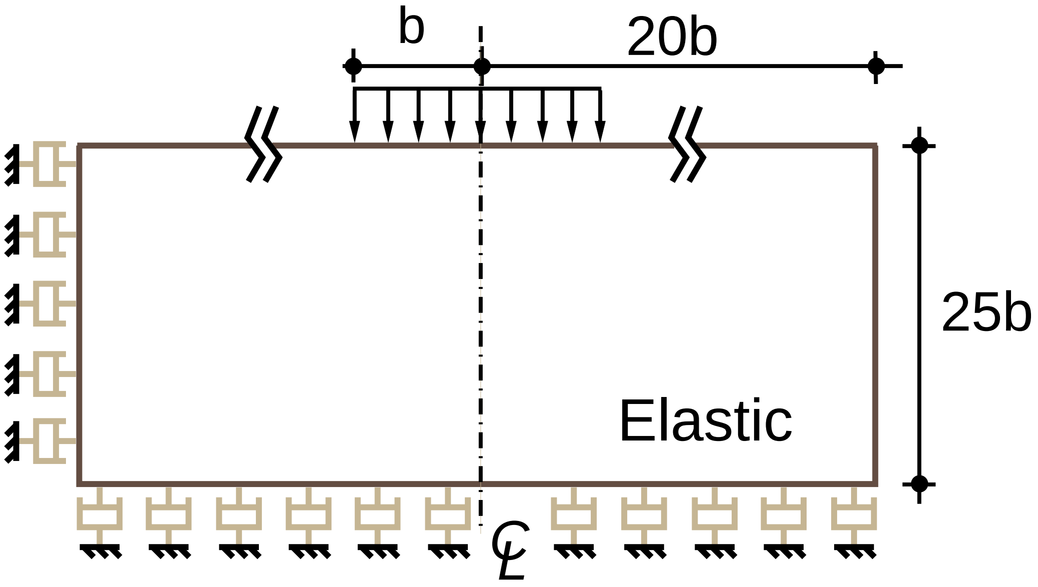
Dashpot model (cross-section)



Classical model (same size as PML model)

PML: 3D example

Extended-mesh model (cross-section)



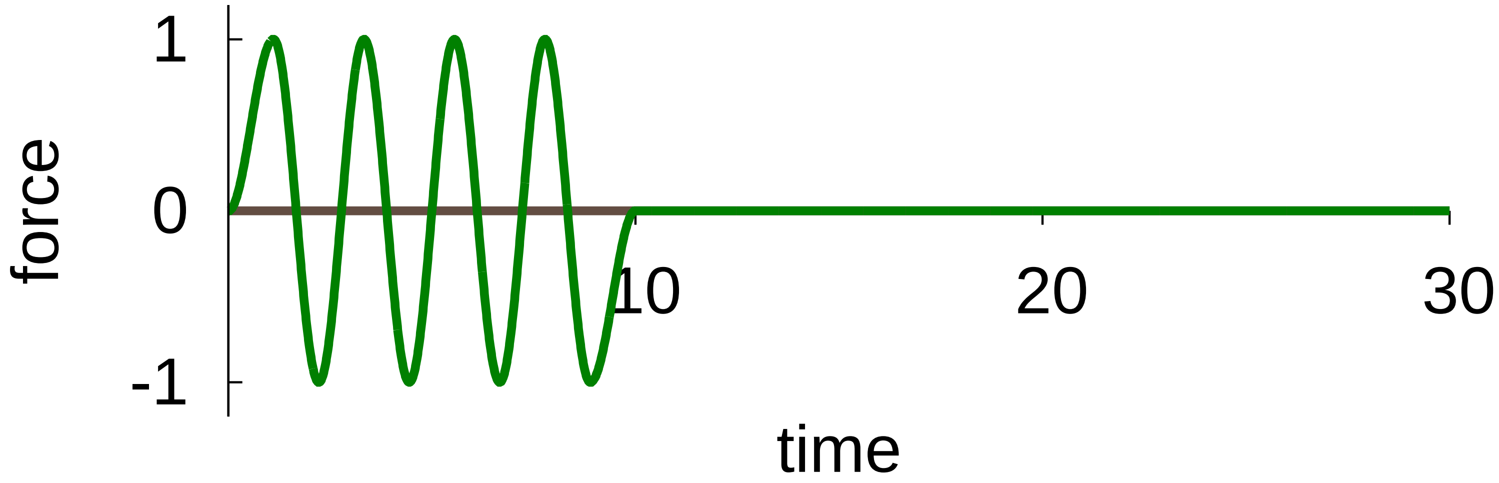
Benchmark model (≈12 elems/wavelength)

PML: elastic waves

PML: 3D example

Excitation and response

Apply vertical force:

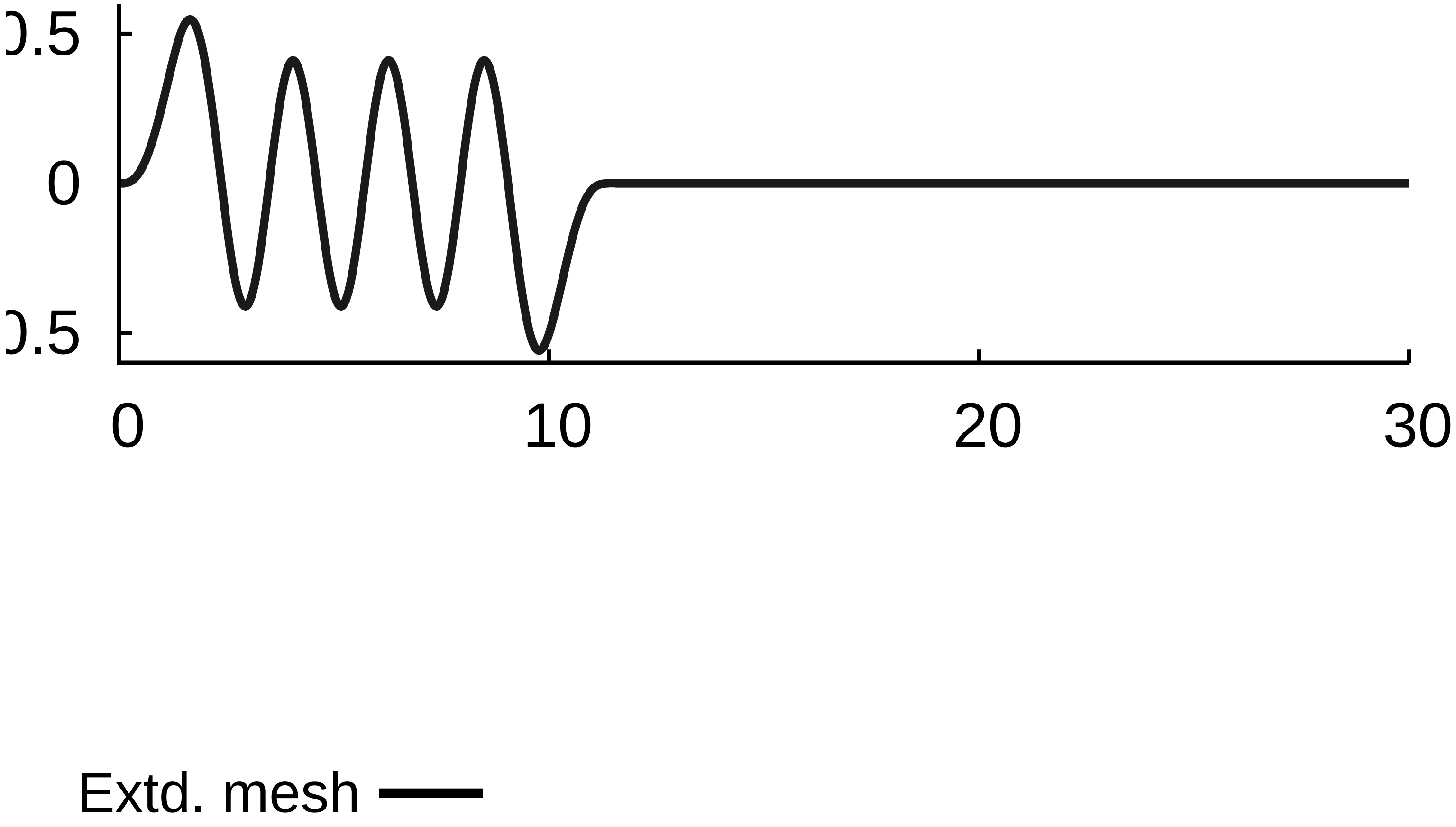


Compute vertical displacement at center and corner

Return time of extd. mesh >30 (normalised time)

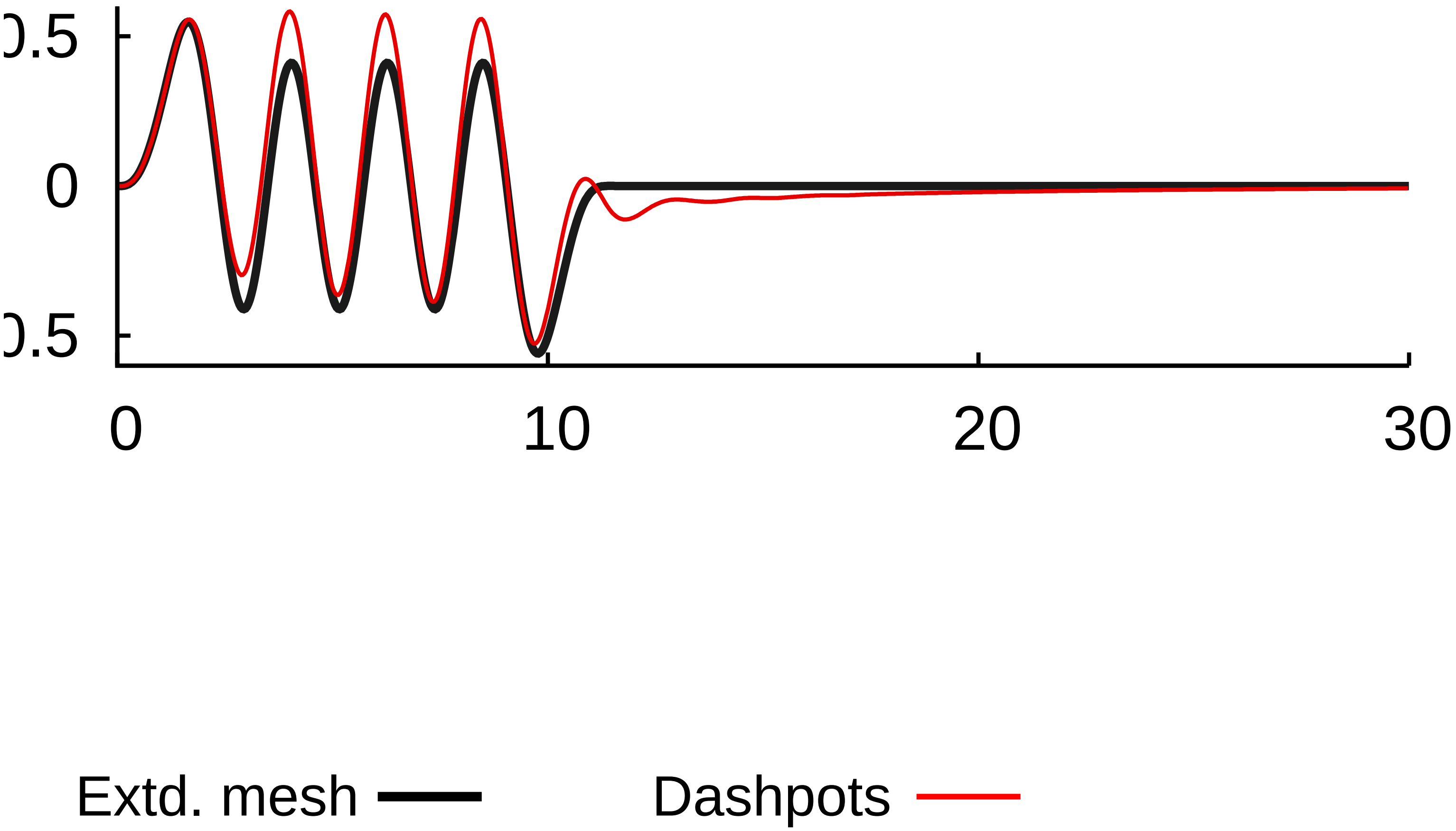
PML: 3D example

Center displacement



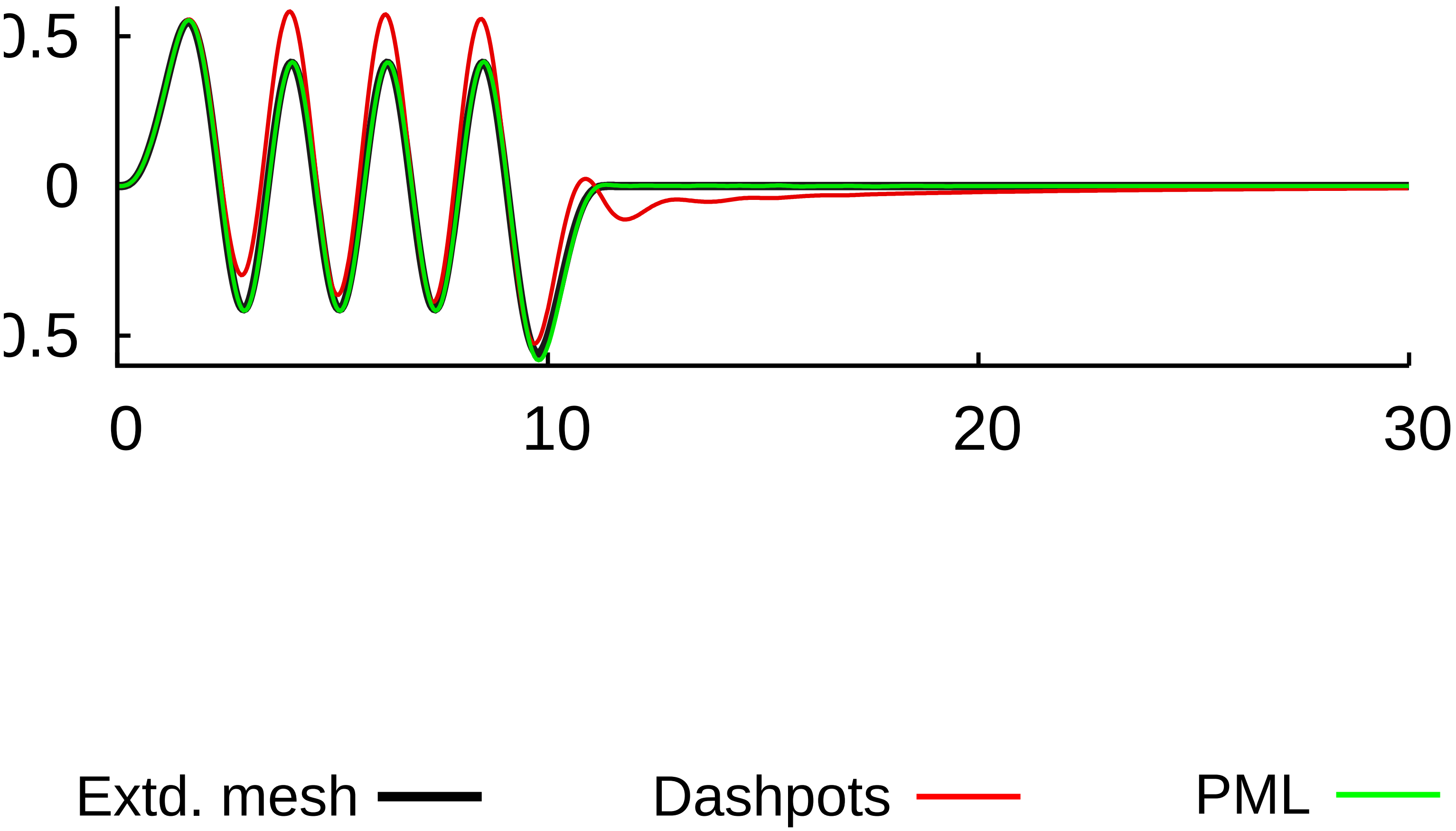
PML: 3D example

Center displacement



PML: 3D example

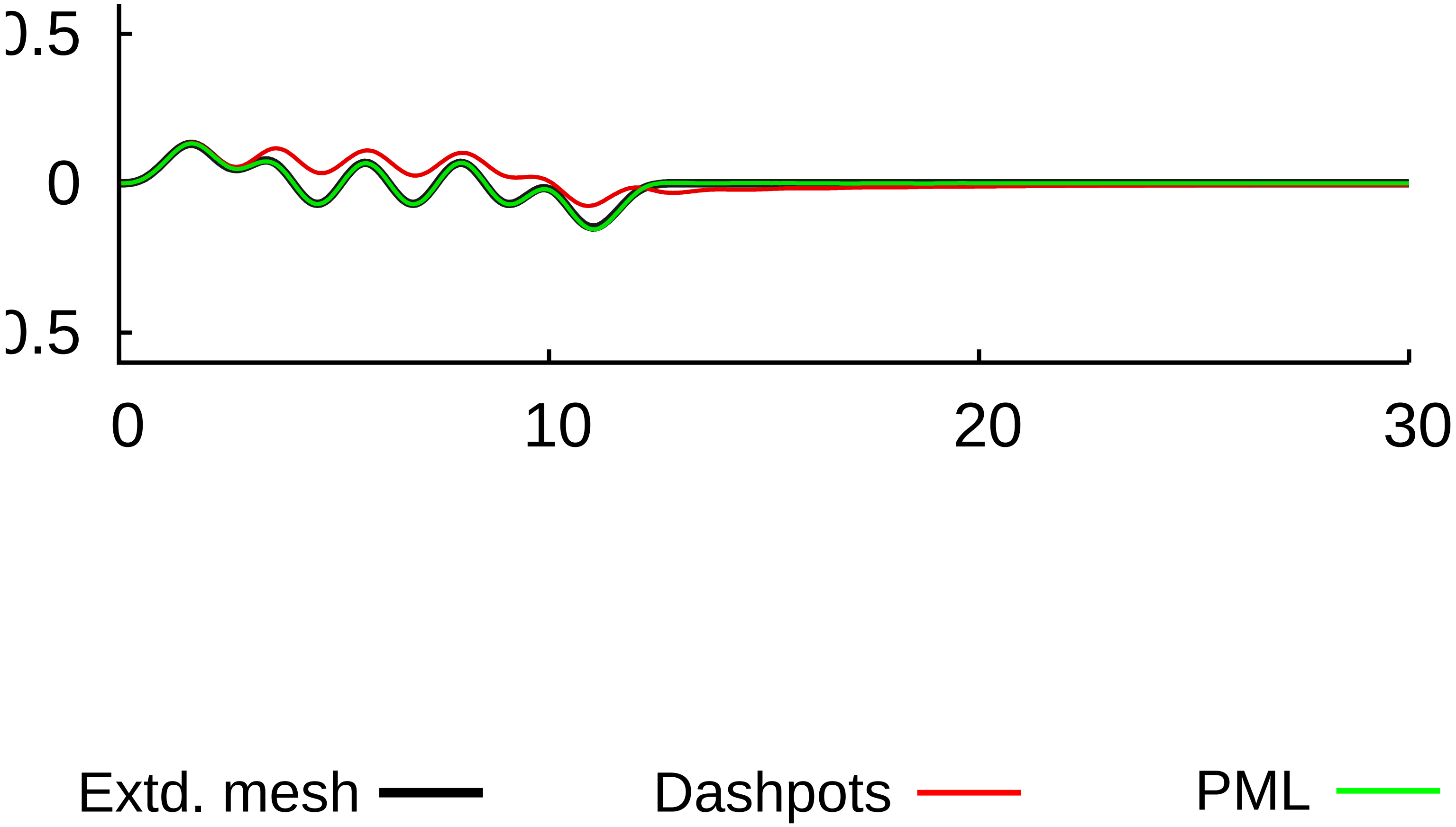
Center displacement



PML: elastic waves

PML: 3D example

Corner displacement



PML: 3D example

Error:

$$\%\text{error} = \frac{\max|u_{\mathrm{PML}} - u_{\mathrm{EXT}}|}{\max|u_{\mathrm{EXT}}|} \times 100$$

Model	Center displacement	Corner displacement
PML	5%	6%
Dashpots	46%	85%

PML: 3D example

Computational costs:

Model	Elements	Time steps	Wall-clock time
PML	4 thousand	600	30 secs
Dashpots	4 thousand	900	15 secs
Extd. mesh	10 million	900	35 proc-hrs

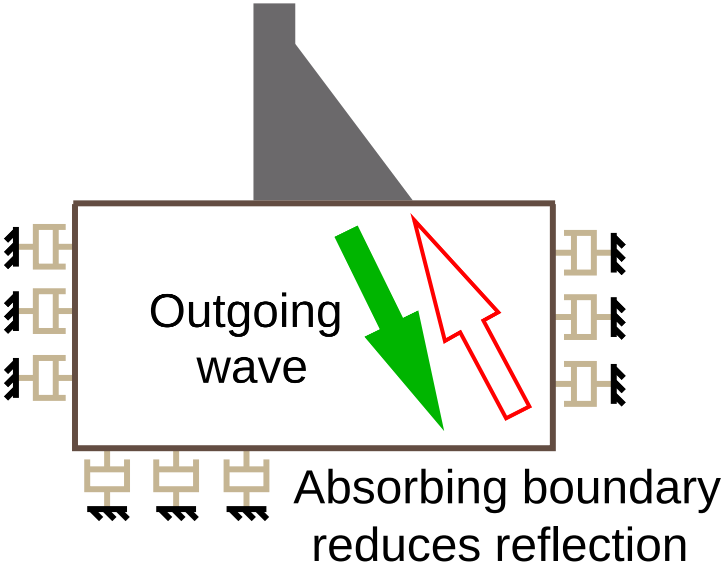
PML and dashpot results computed on desktop workstation

Extd. mesh results required a supercomputer and parallelised and specially-optimised code

➠ PML guarantees accurate results at low cost

GO BACK

Dam on bounded foundation with absorbing boundary



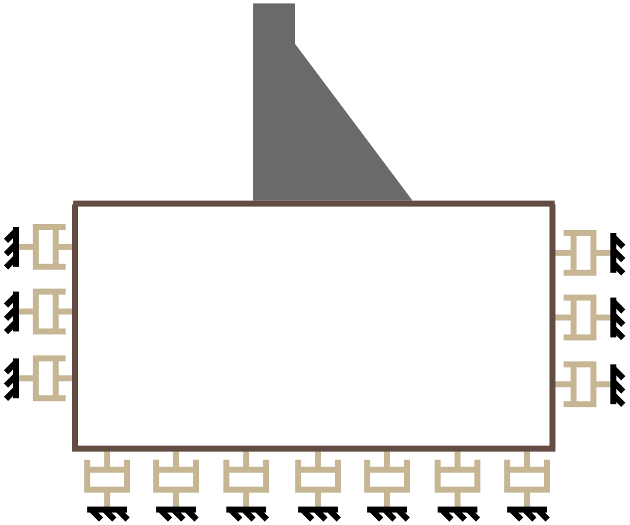
Absorbing boundary simulates unbounded foundation

Two questions

How do we:

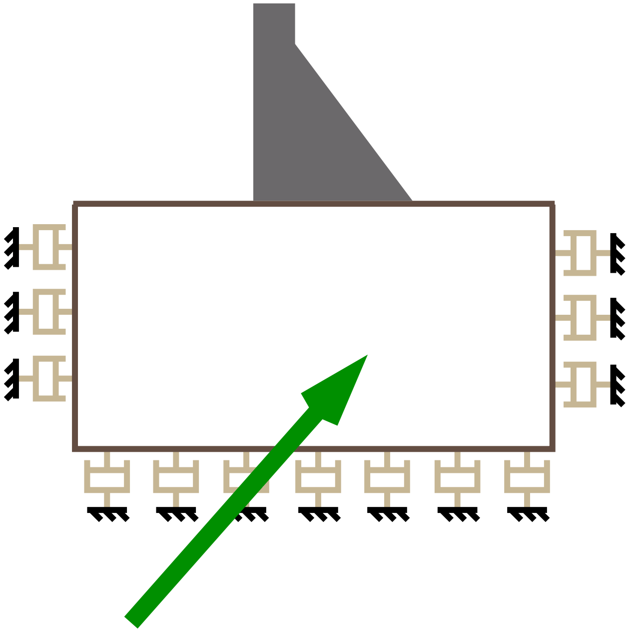
1. apply the ground motion?
2. account for the unbounded reservoir?

Applying the ground motion



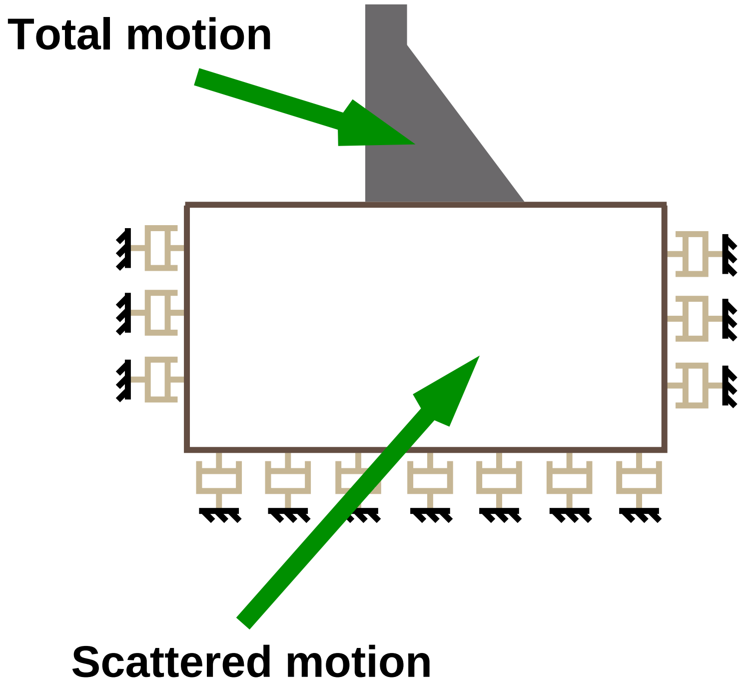
Dam on bounded foundation with absorbing boundary

Applying the ground motion



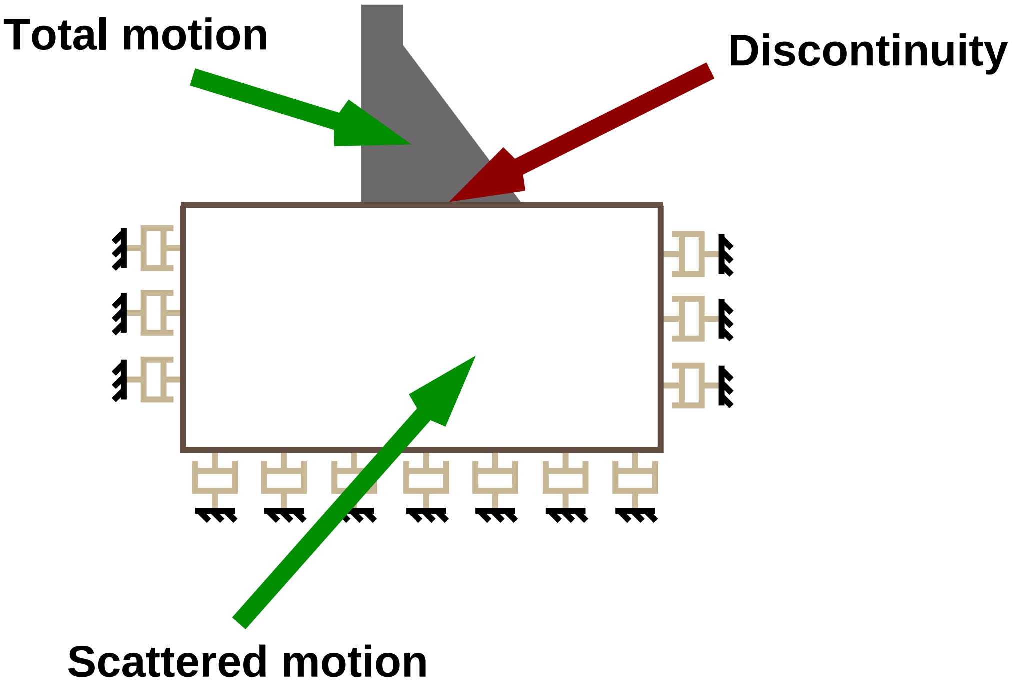
Foundation has scattered motion . . .

Applying the ground motion



but dam has total motion

Applying the ground motion



Discontinuity at interface creates effective forces

Applying the ground motion

Discontinuity is exactly the free-field ground motion
$\Rightarrow$ effective forces depend only on
free-field ground motion at the interface

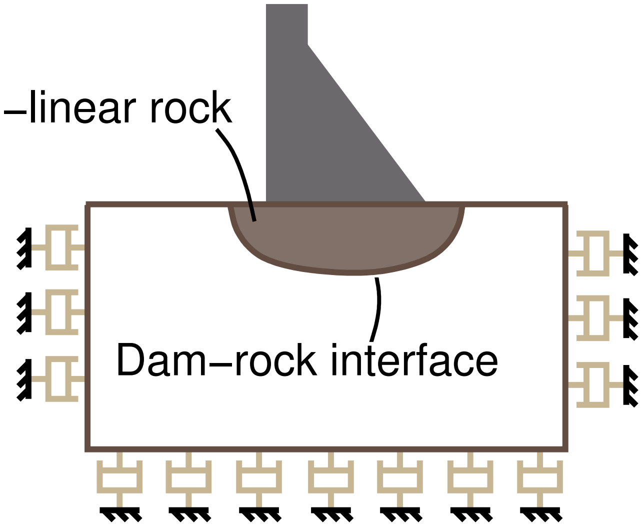
Effective seismic input method

[Herrera, Bielak (1977); Bielak, Christiano (1984)]
compute effective seismic forces at the interface
using only free-field ground motions at the interface

$\Rightarrow$ no deconvolution is necessary

Dealing with non-linear rock

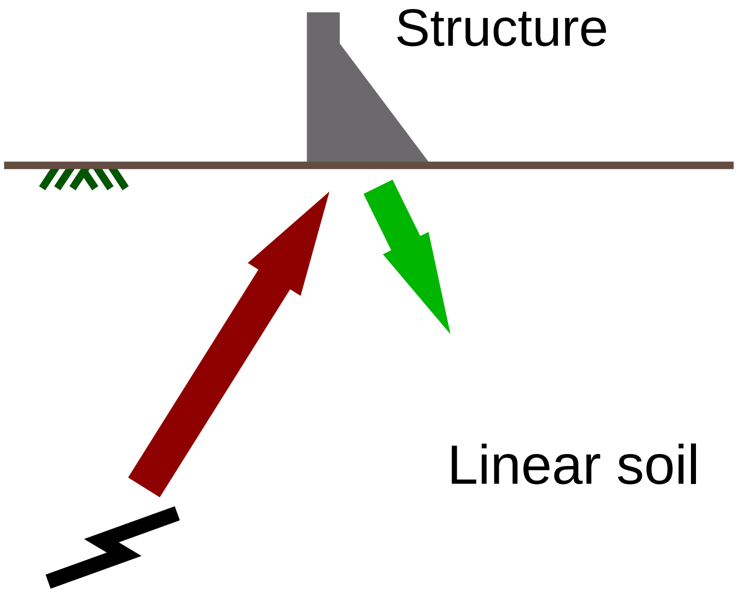
Assume that non-linearity is only near the dam



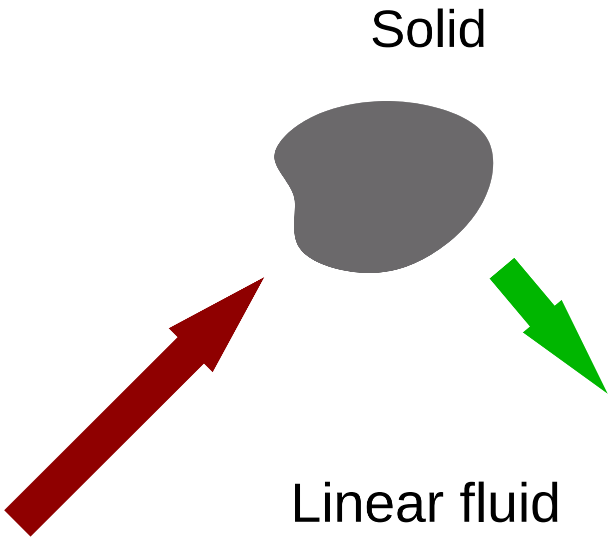
Redefine dam-rock interface to include non-linearity

Dam-water-foundation rock interaction

Scattering analysis



Soil–structure interaction



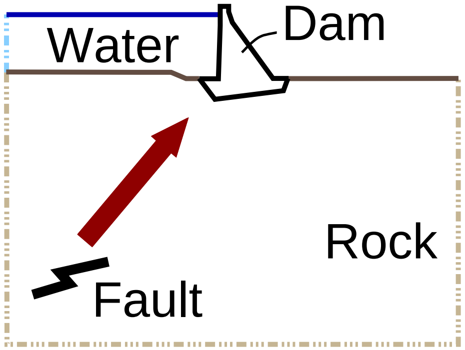
Acoustic scattering

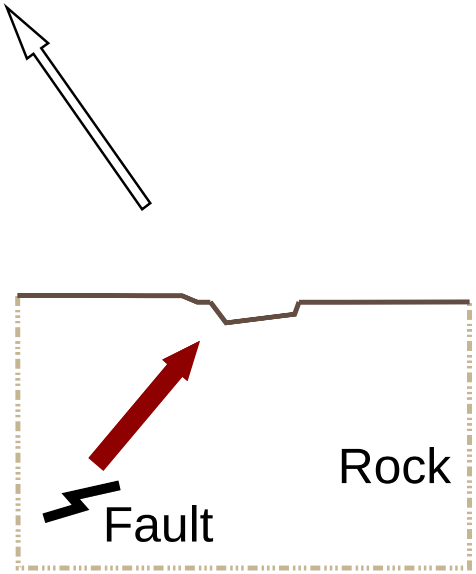
Linear background medium disturbed by solid structure

Only linearity is important, not physics

Dam-water-foundation rock interaction

Scattering analysis [Basu-Chopra-Taylor (2004)]



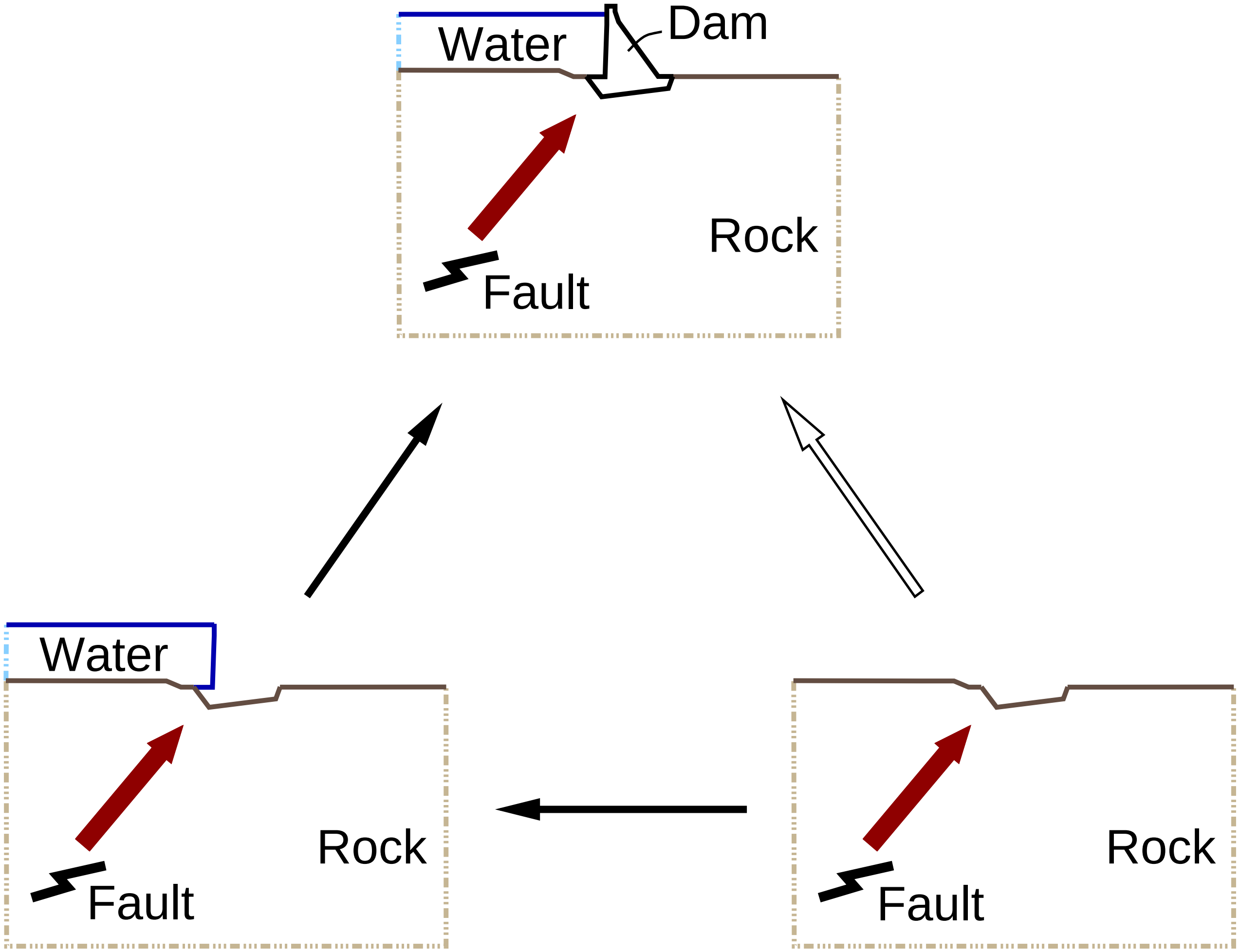


NEED

LINEAR MEDIUM

Dam-water-foundation rock interaction

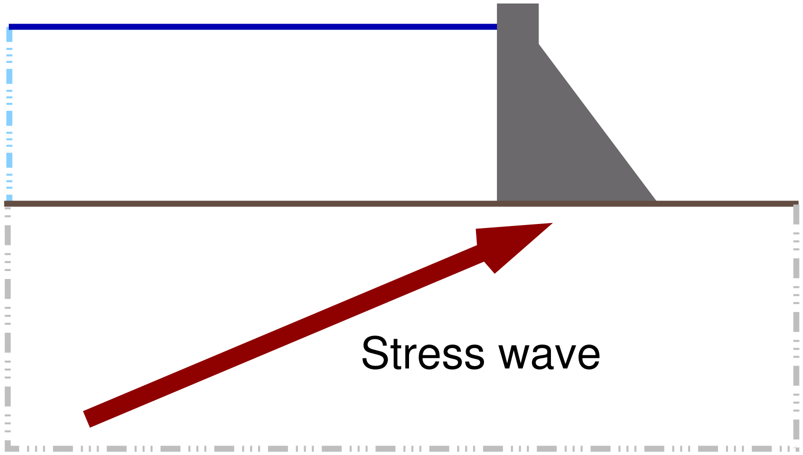
Scattering analysis [Basu-Chopra-Taylor (2004)]



Two-step analysis using auxiliary water-rock system

Dam-water-foundation rock interaction

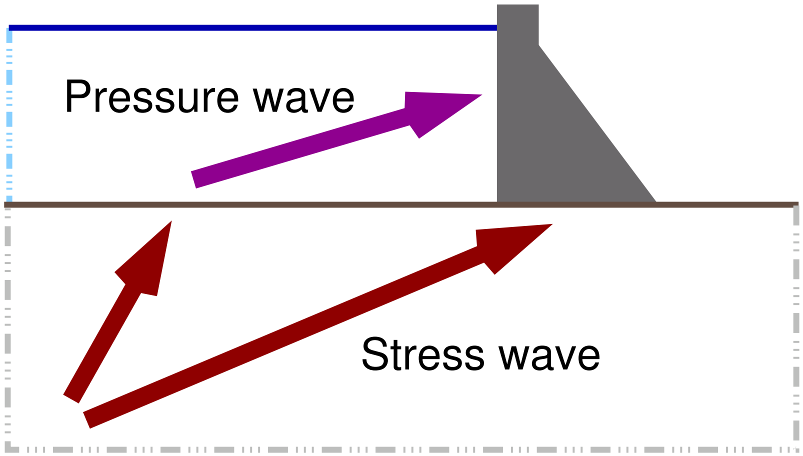
Scattering analysis



Earthquake wave reaches the dam through the ground...

Dam-water-foundation rock interaction

Scattering analysis



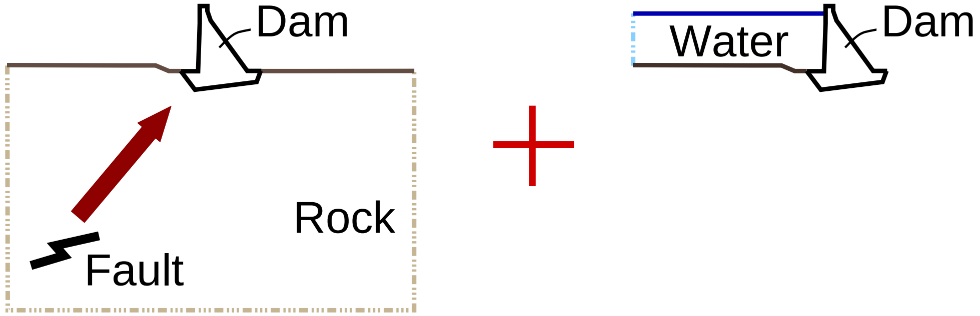
...and the impounded water

Auxiliary system brings in effect of far-field pressure waves

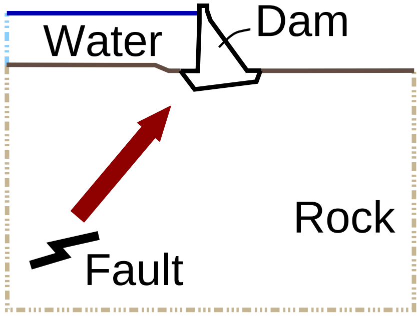
Dam-water-foundation rock interaction

A new viewpoint

Previously: soil-structure + fluid-structure interaction



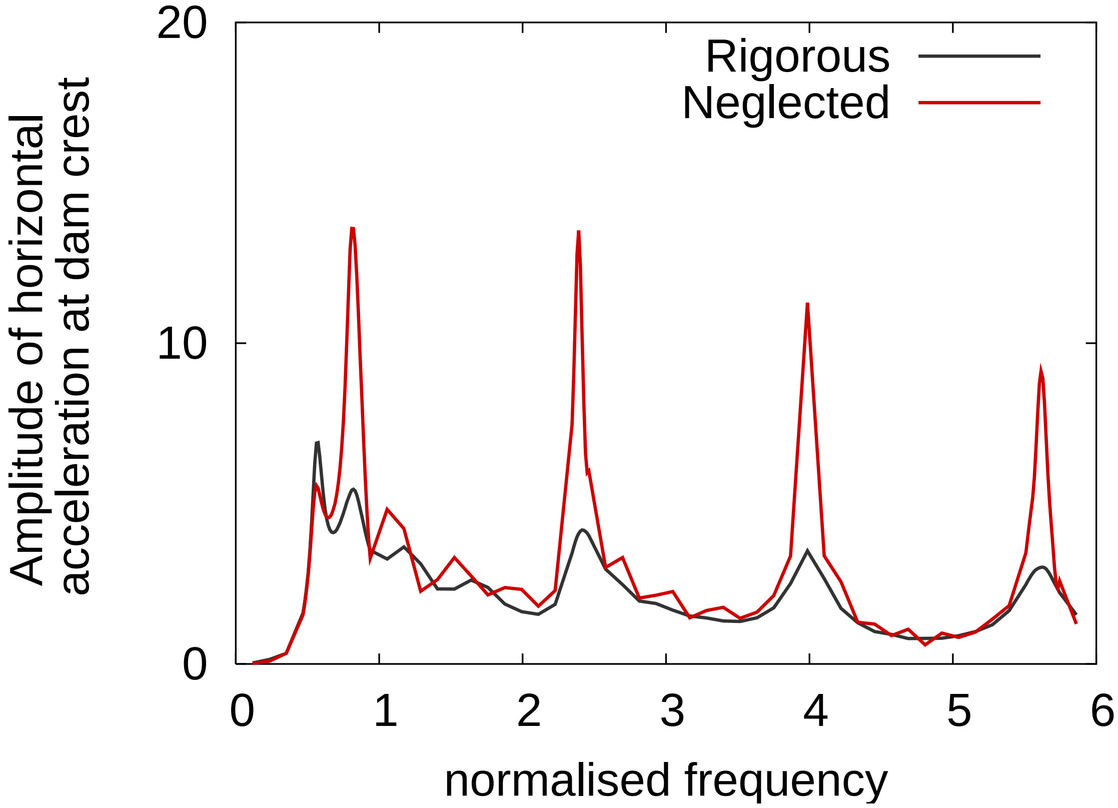
Now: coupled multi-physics scattering problem



Dam-water-foundation rock interaction

Numerical discovery

Water-foundation rock interaction can affect response if reservoir-bottom absorption is low



Dam-water-foundation rock interaction

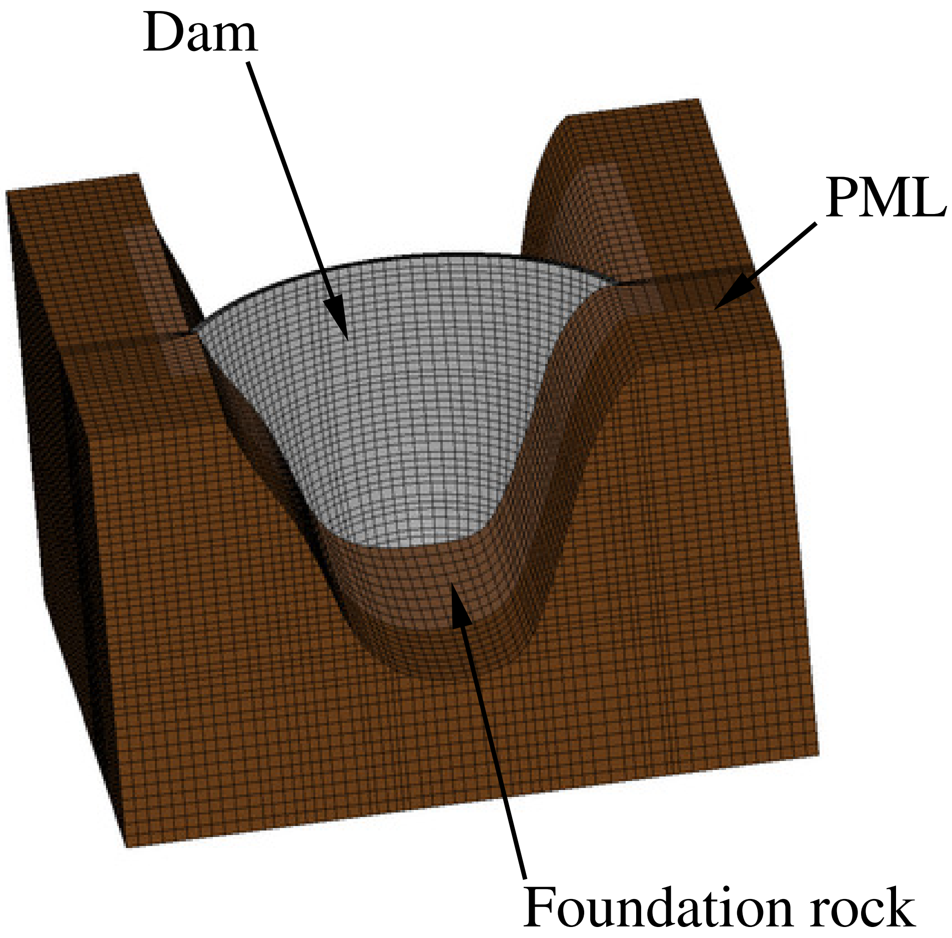
Transient analysis procedure

- Equivalent to propagating earthquake from fault to site
- Fully finite-element procedure
- Includes all significant interactions
- Uses PMLs for foundation rock and water

Numerical validation:

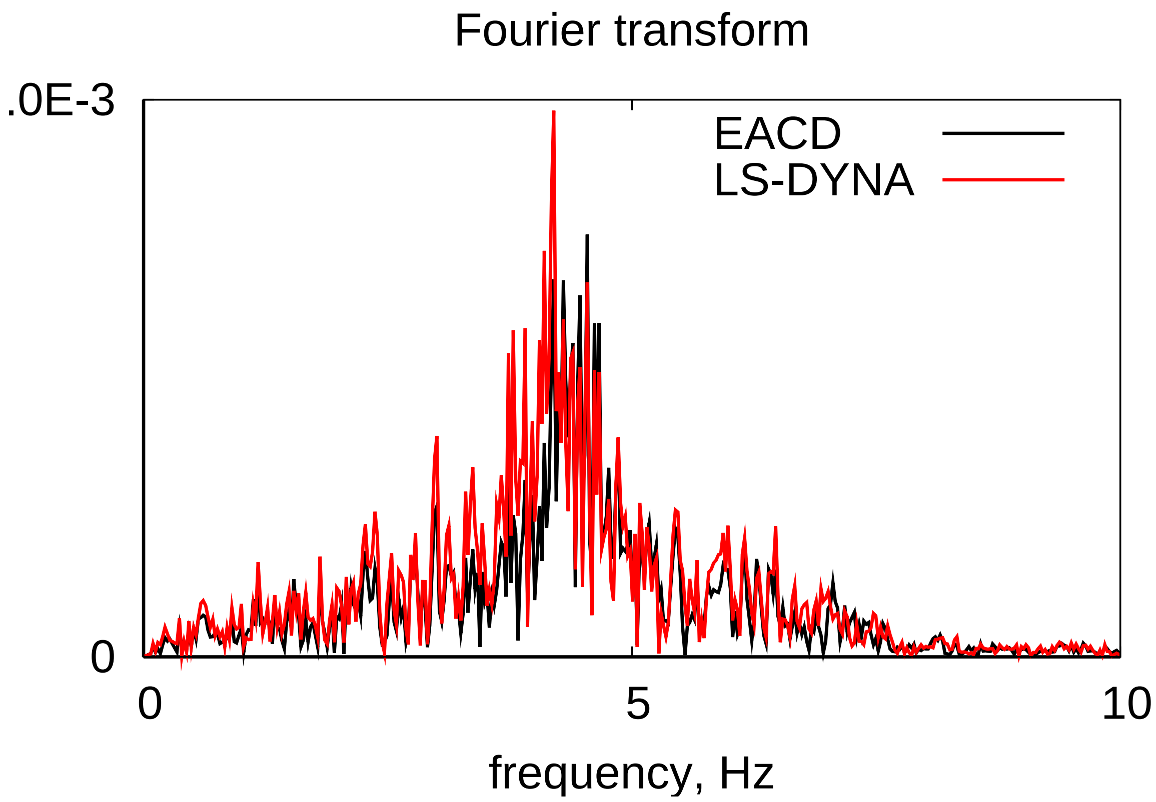
- Complete for two-dimensional analysis, against EAGD-84
- Ongoing for three-dimensional analysis, against EACD-3D-2008

Validation for Morrow Point Dam

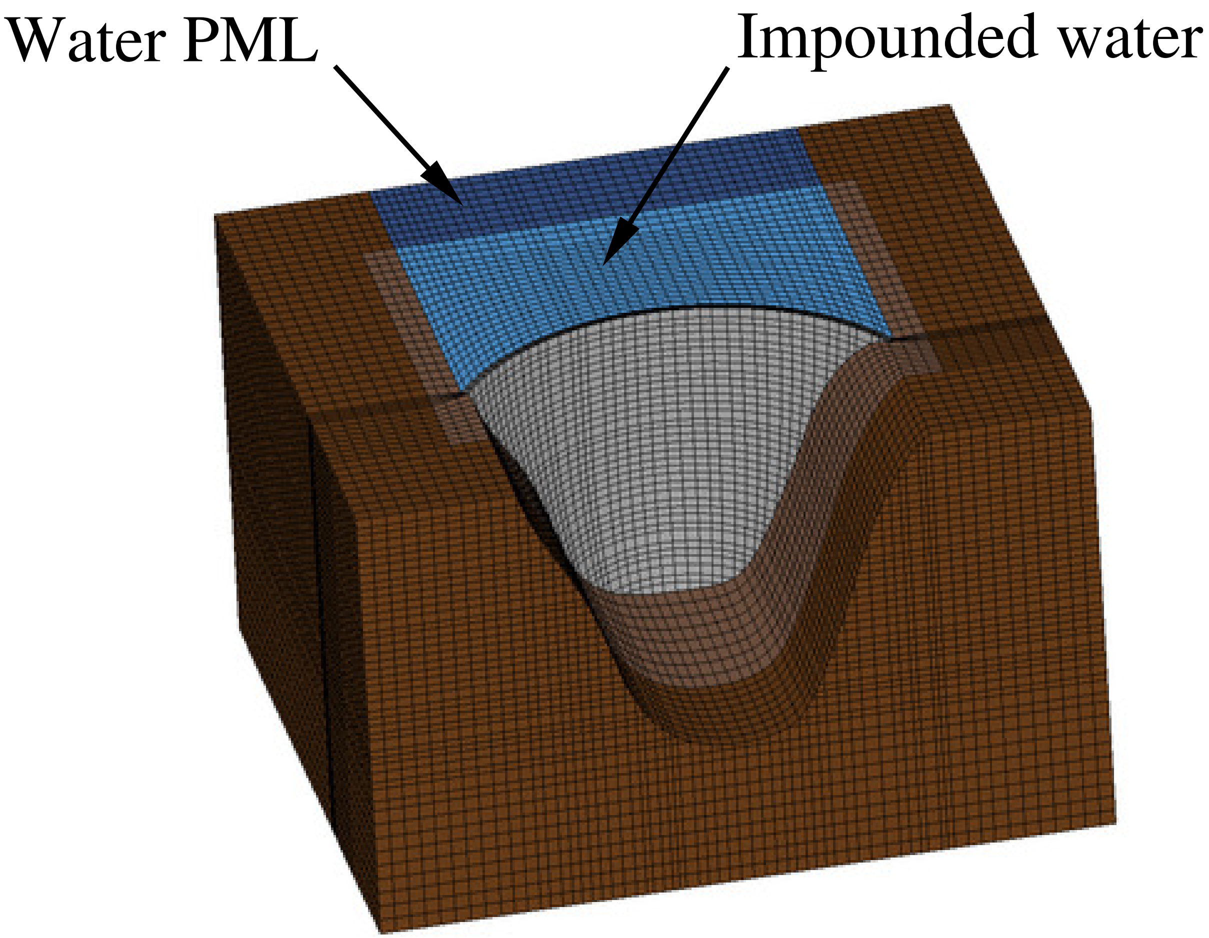


Dam-foundation rock model

Validation for Morrow Point Dam



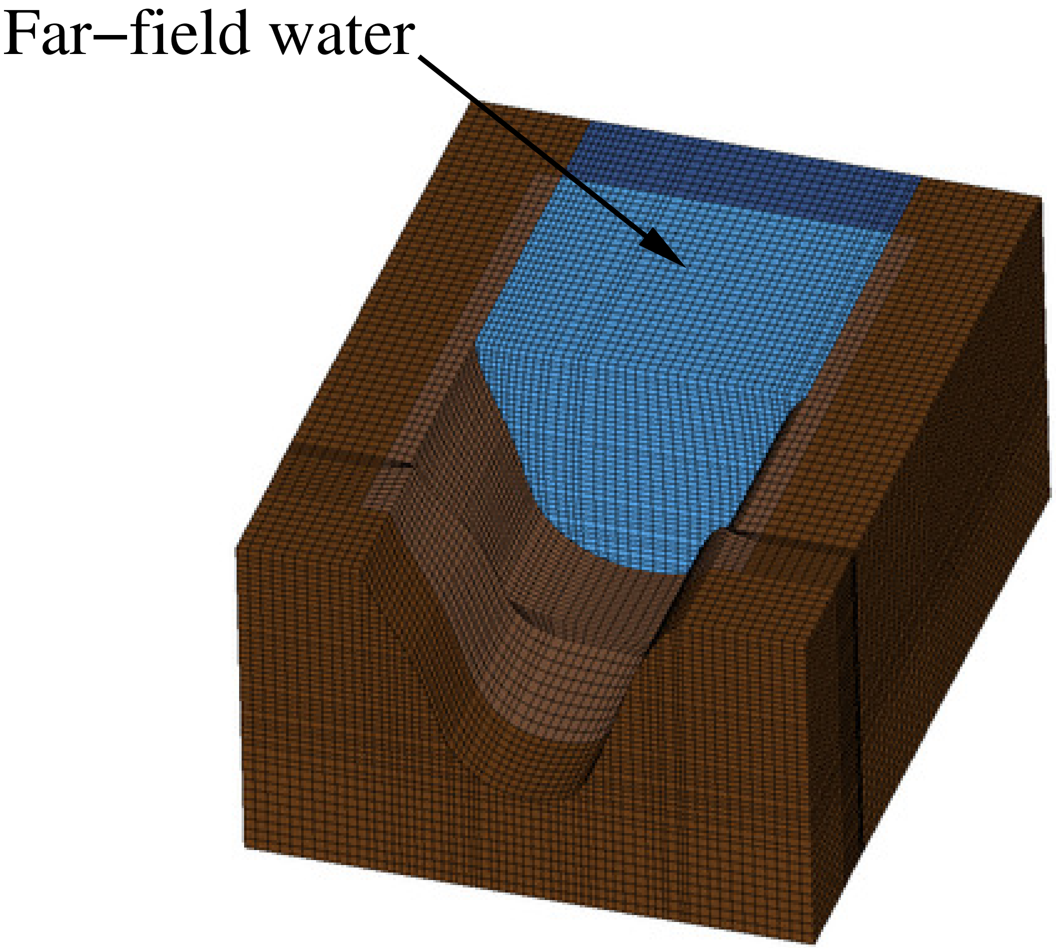
Validation for Morrow Point Dam



Dam-water-foundation rock model

Dam-water-foundation rock interaction

Validation for Morrow Point Dam



Auxiliary water-foundation rock model

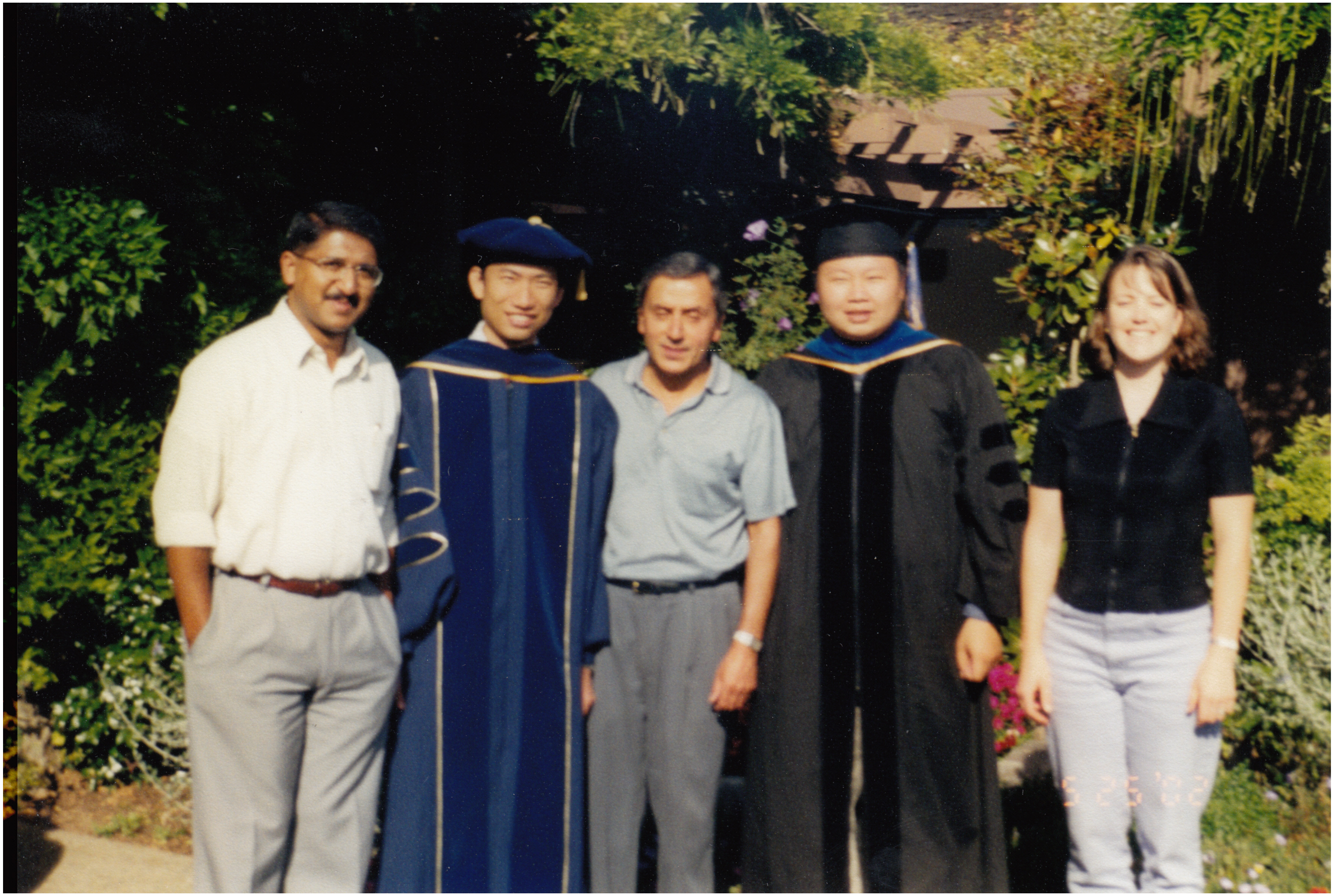
Validation for Morrow Point Dam

Current status:

Work is in progress on:

- Validation of full model
- Specification of input ground motion

Some personal photos



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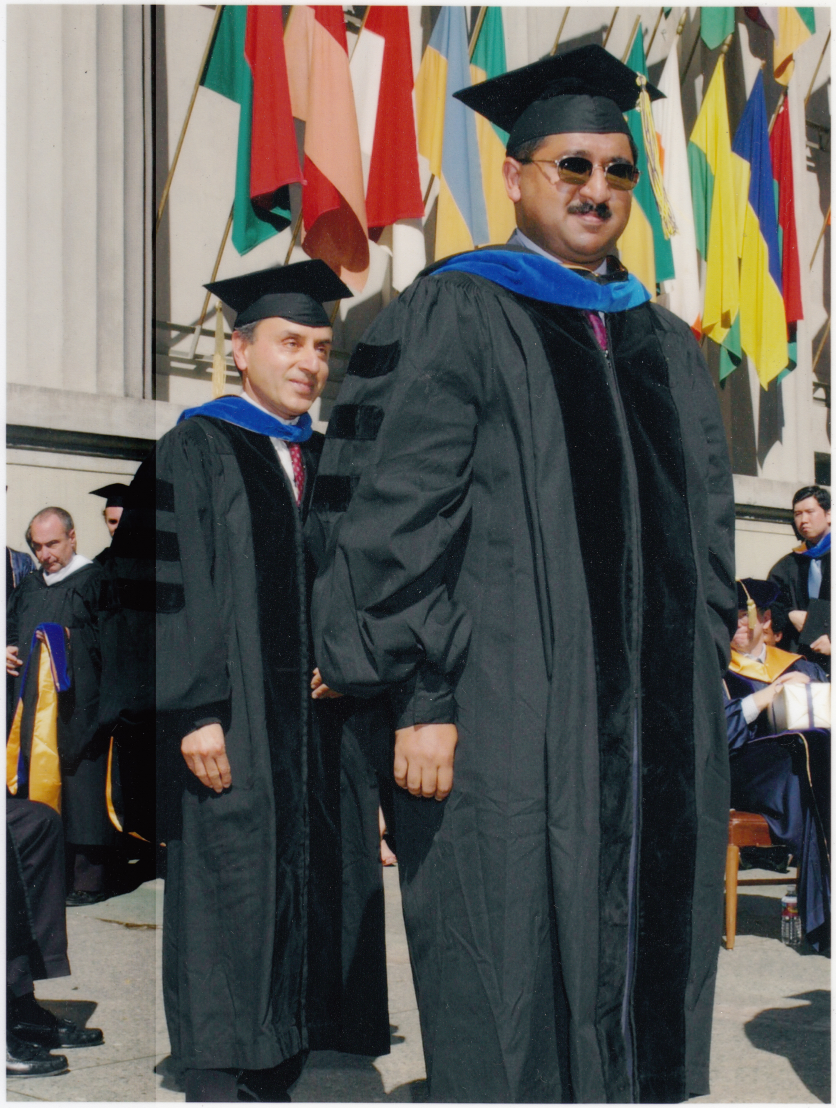
Some personal photos

Some personal photos



UC Berkeley
College of Engineering Commencement
May 21, 2005

Bob Knight PHOTO