Direct Finite Element Method for Seismic Soil(Rock)-Structure Interaction

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Outline

- Methods of analysis
- Requirements for direct method
- Free-field motion
- Other considerations

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Types of dynamic soil-structure interaction analyses

No soil-structure interaction

Equivalent linear springs

Linear or equivalent-linear, fully-coupled SSI

Nonlinear fully-coupled SSI

Direct FE method

Increasing:

- Rigor
- Complexity
- Computation time
- Cost

Motivation – why do dynamic SSI analyses?

- More realistic representation of the system
  - Presence of the structure affects earthquake motion in the soil (kinematic interaction)
  - Presence of soil affects vibration of the structure (inertial interaction)
- (Often) a significant source of reserves in design calculations
  - Important for structures to be designed for extreme loading events (e.g. ≥ 10,000 year RP earthquakes)
  - Most significant for soft soils, but can also be important for rock sites (especially with low-moderate Vs)

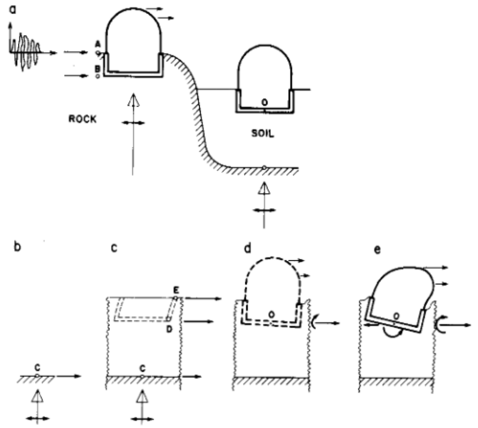


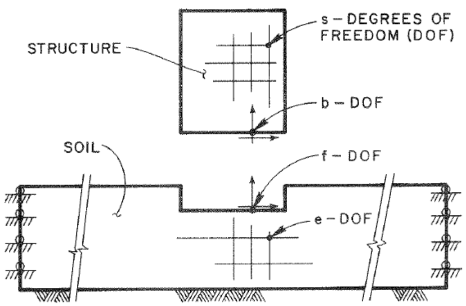
Figure 1-2 Seismic response of structure founded on rock and on soil. (a) Sites; (b) outcropping rock; (c) free field; (d) kinematic interaction; (e) inertial interaction.

From Wolf (1980)

Methods of analysis for dynamic SSI

Substructure Method

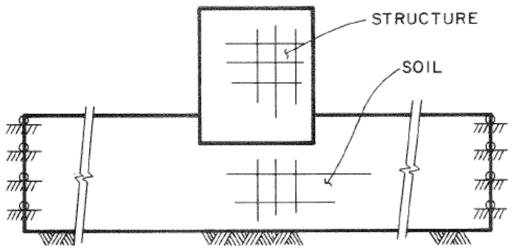
- Models each domain separately
- Rigorous treatment of unbounded domains
- Frequency-domain solution with FFT (computationally very efficient)
- Special-purpose software
- Restricted to linear elastic analysis



(b) SUBSTRUCTURE MODEL

Direct Method

- The available/preferred procedure in almost all commercial FE software
- Applicable to nonlinear analysis
- Special treatment of boundaries
- More time-consuming analyses (time domain)



(a) DIRECT MODEL

Outline

- Methods of analysis
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- Free-field motion
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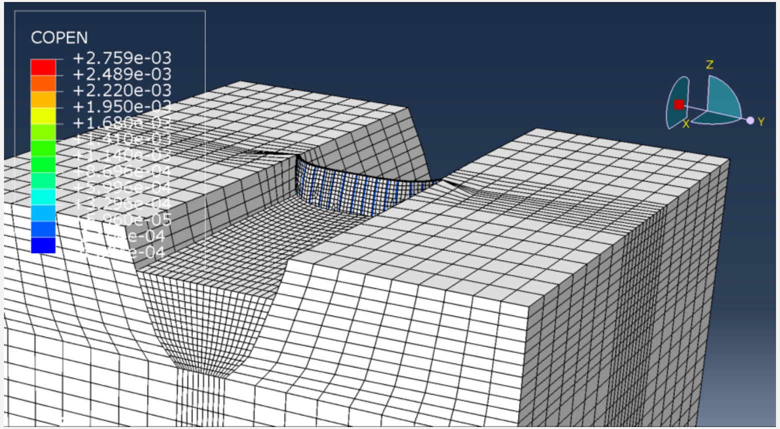
Requirements for direct method

1. Suitable FE model of soil-structure system
2. An absorbing boundary to simulate unbounded domains
3. Method for specifying loads to the FE model

Finite element model of soil-structure system

Considerations

- Mesh (element type, size, etc.)
- Constitutive models and material input parameters
- Interfaces
- Dynamic loads
- Boundary conditions
- Initial conditions
- Stability and convergence
- +++

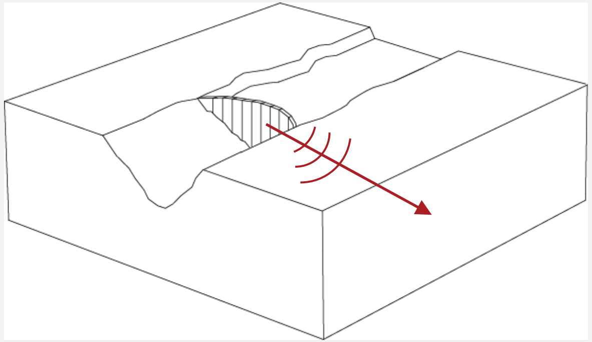


SSI model of dam-water-foundation system

Absorbing boundaries

Mechanism

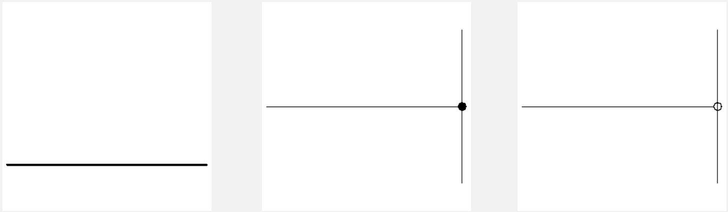
- Outwards propagating waves (generally) do not return
- Commonly referred to as "radiation damping" or "geometric damping" (although strictly speaking not damping)



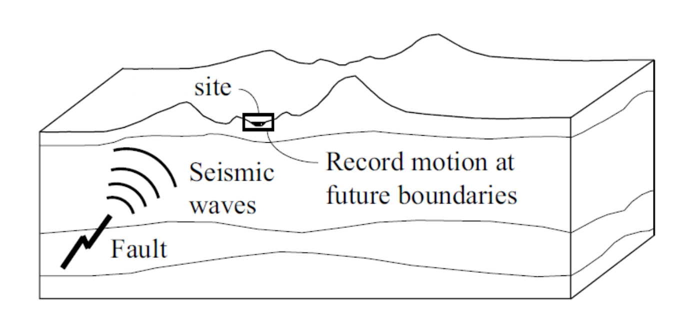
Types of absorbing boundaries

- Global / consistent (exact) – frequency dependent, rarely used in commercial codes
- Local (approximate) – e.g. viscous dampers, cone boundaries, PML, etc.
- For direct FE method – viscous dampers (dashpots) chosen

Absorbing boundary **Fixed boundary** **Free boundary**

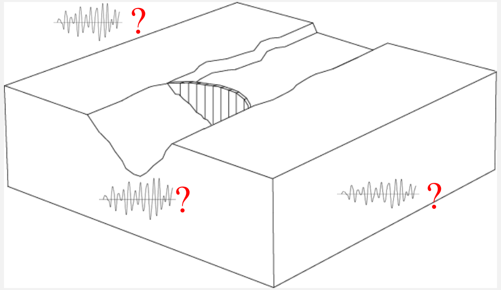


Application of seismic loads



Earthquake loads

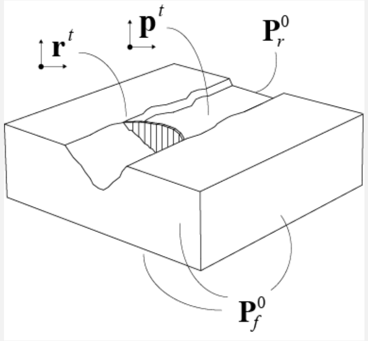
- Waves propagating from a fault to the site
- Boundaries need to absorb the outgoing waves and transmit incoming waves
- Need to specify spatially varying effective earthquake forces at all model boundaries



- **How to compute these forces?**

Equations of motion for direct FE method

Equations of motion derived using principles of dynamics (see papers for derivation):



$$\mathbf{m}\ddot{\mathbf{r}}^t + \left[\mathbf{c} + \mathbf{c}_f\right]\dot{\mathbf{r}}^t + \mathbf{f}(\mathbf{r}^t) = \mathbf{R}^{st} + \mathbf{P}_f^0$$

Where the *effective earthquake forces* are

$\mathbf{P}_f^0 = \mathbf{R}_f^0 + \mathbf{c}_f \dot{\mathbf{r}}_f^0$, applied at the foundation boundaries

These earthquake forces only depend on free-field motion at the foundation boundaries!

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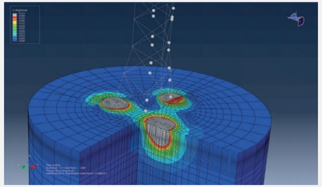
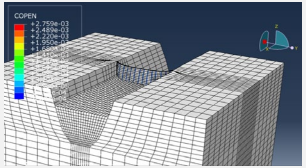
We now have all three ingredients for dynamic SSI

1 An appropriate finite element model of the soil-structure interacting system





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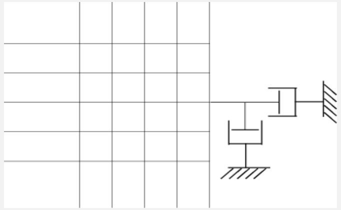
2 An absorbing boundary to simulate the unbounded foundation domain

Viscous damper



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3 A method for specifying loads (e.g. seismic input) to the FE model

$$\sigma^t(t) = \underbrace{\sigma^0(t) + c_p\dot{u}^0(t)}_{\text{1. Effective earthquake forces at boundary}} - \underbrace{c_p\dot{u}^t(t)}_{\text{2. Viscous damper at boundary}}$$

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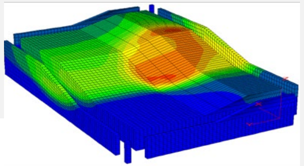
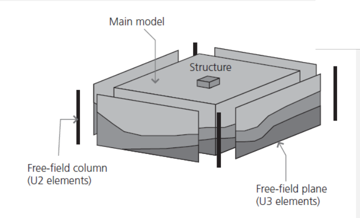
Two ways to implement effective earthquake forces

Automatic treatment with free-field boundaries

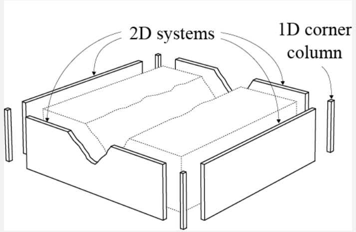
- Forces applied automatically using free-field boundary elements
- A few FE codes have such elements available (e.g. FLAC, Plaxis2D/3D)





Compute effective earthquake forces separately and apply to model

- Can be implemented independently of the FE code
- Large book-keeping requirements, especially for 3D systems
- Some “user-elements” are publicly available (e.g. for ABAQUS)



Outline

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- Free-field motion
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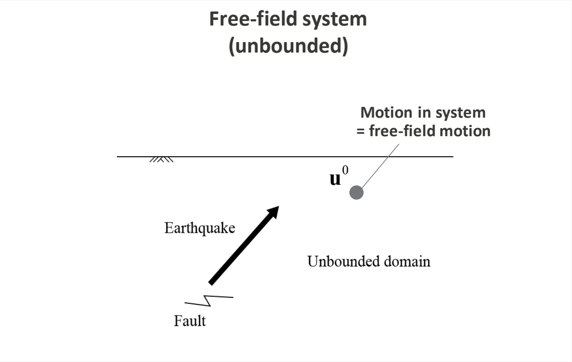
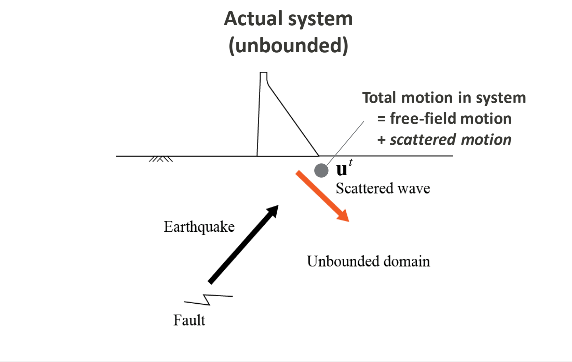
What is "free-field" response

"Free-field" state defined as

- The system before the structure was constructed or excavation had started
- Does not (necessarily) correspond to any physical state of the system
- In theory, any admissible free-field system can be chosen (but some are smarter than others)





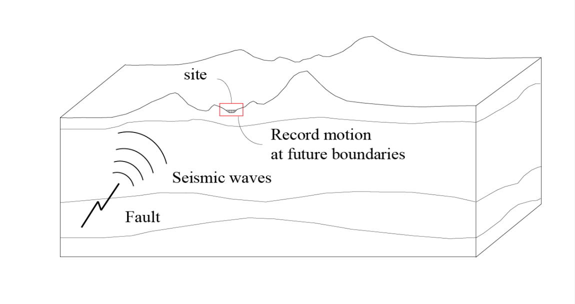
Obtaining the free-field motion

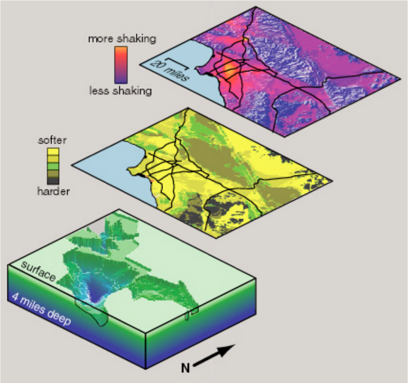
Most general approach: Physics based 3D models simulating fault rupture and wave propagation

Currently being used for large SSI simulations of highly populated areas (e.g. LA basin)

Impractical for most projects

- Limited information available regarding faults, geological materials and local site conditions
- Need to model every dominating fault rupture
- Difficult to define motions in high-frequency range needed for concrete dams and NPPs





SCEC 3D simulation of LA basin

Obtaining the free-field motion

Most common approach: Obtain motion at boundaries from one (or several) assumed surface motion(s)

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- Can be obtained from PSHA
- Large databases of motions are available
- Motions are representative for a flat site (often from basement of a building or at rock outcrop)
- Deconvolution to obtain base input motion

- **Assumes vertically propagating waves**

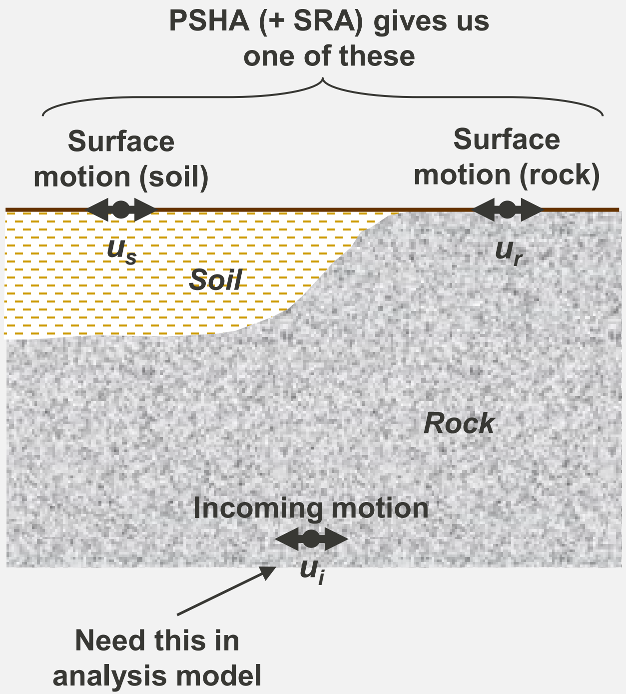

Figure adapted from Kramer

Vertically propagating waves (NPP example)

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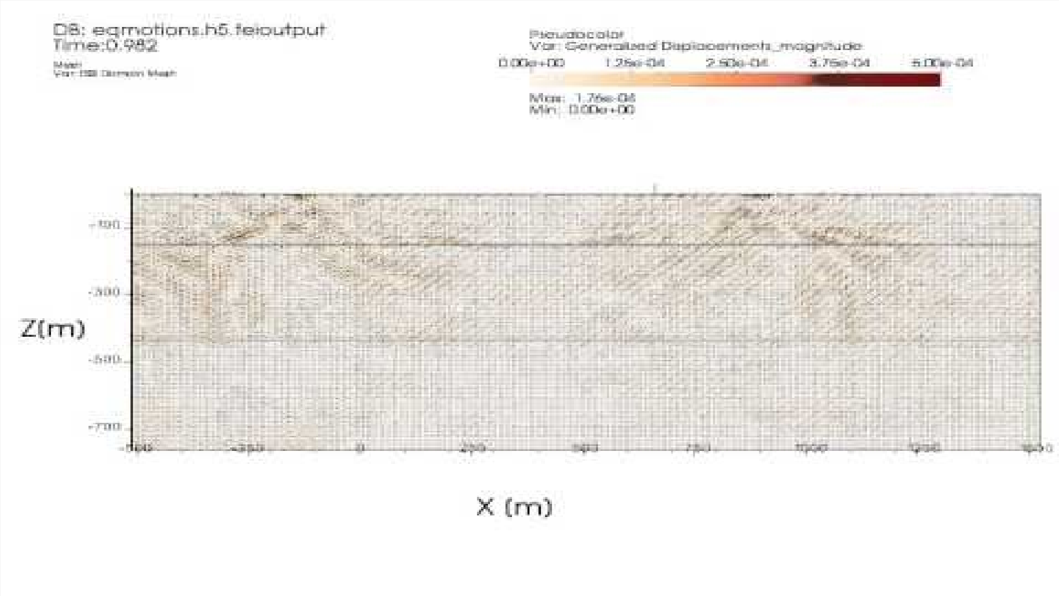
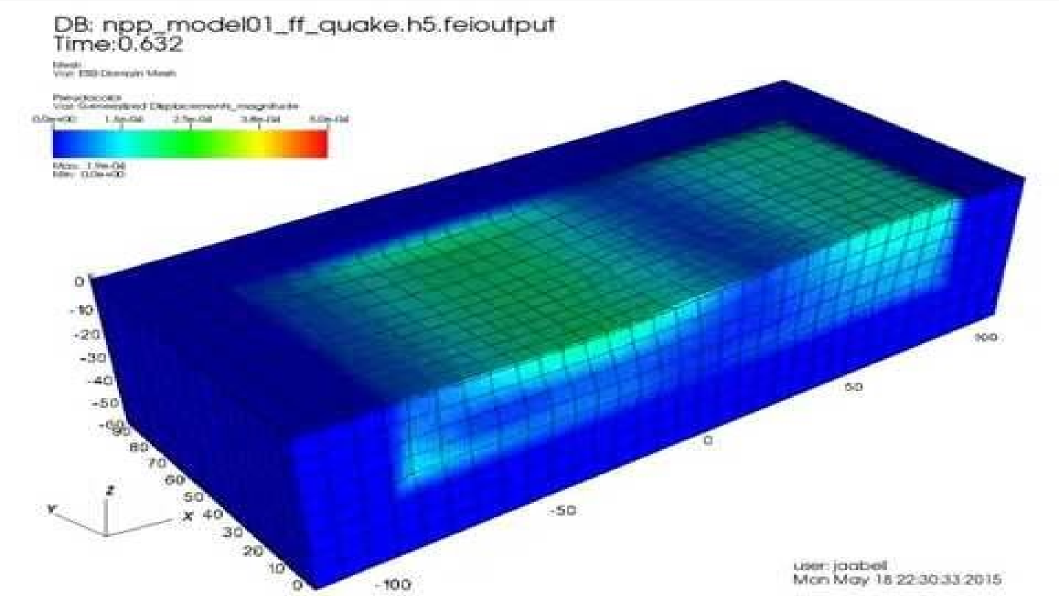


Credit: Professor Boris Jeremic, UC Davis

http://sokocalo.engr.ucdavis.edu/~jeremic/6D_vs_1D_ESSI_for_NPPs/

Vertically propagating waves (NPP example)



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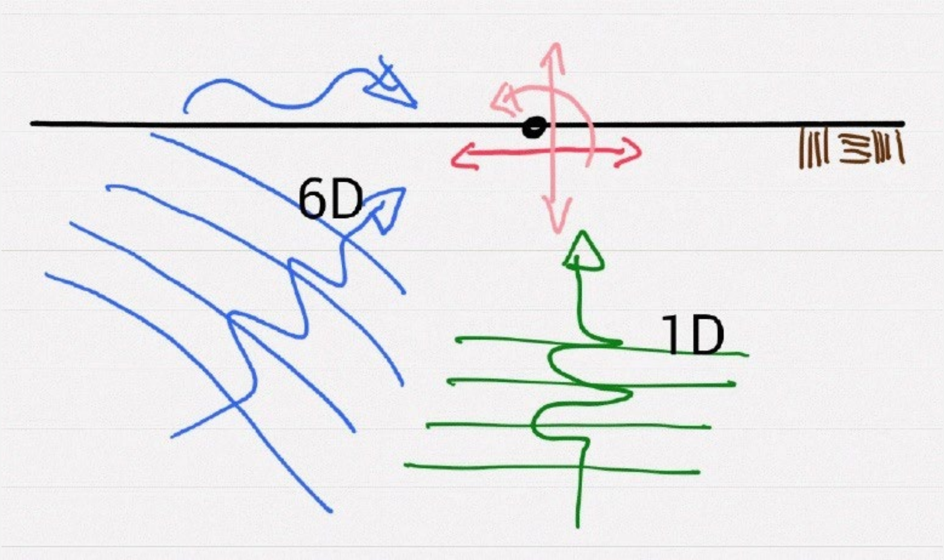

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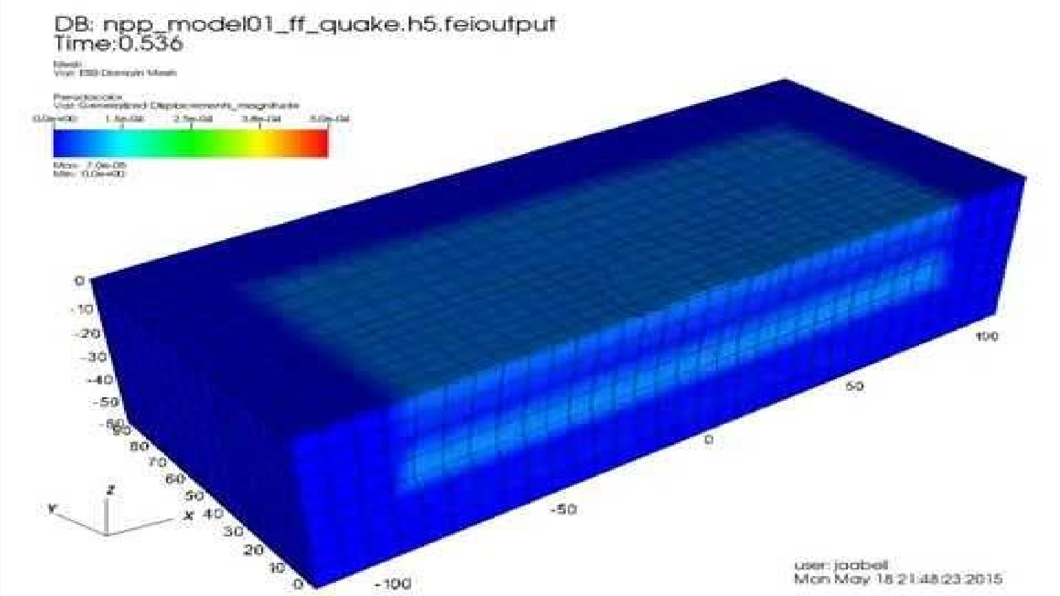

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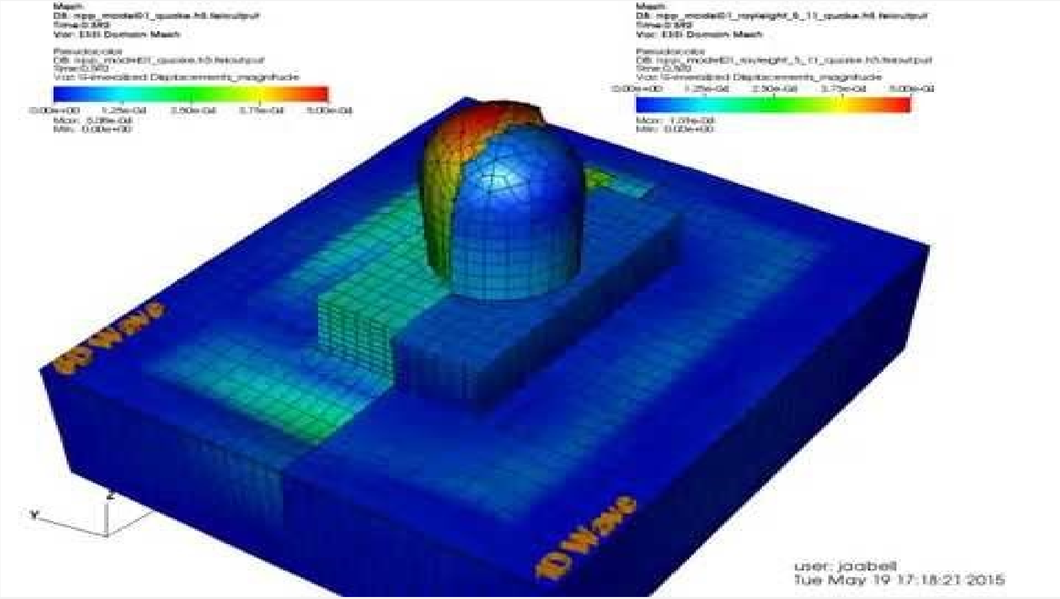

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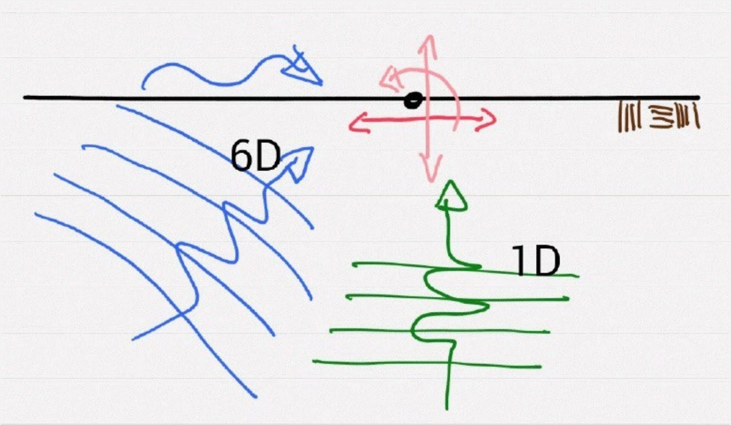
Free-field motion – considerations

- Vertically propagating waves clearly a major simplification of reality – but currently the only pragmatic approach we have
- Should consider investigating various incidence angles for structures that are sensitive to surface waves / rocking motion



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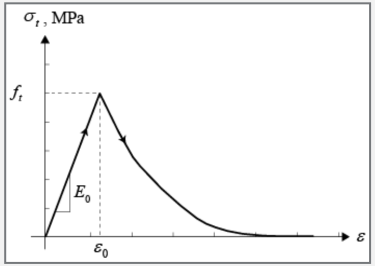
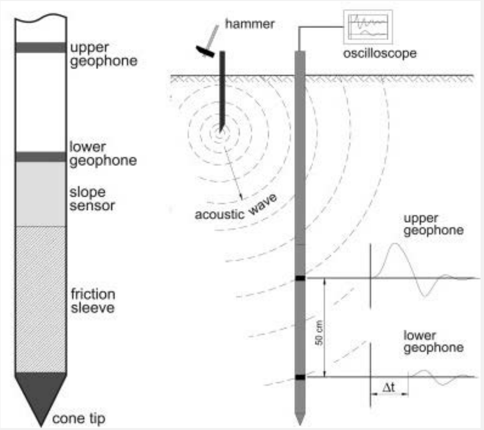
Other considerations: Dynamic input parameters

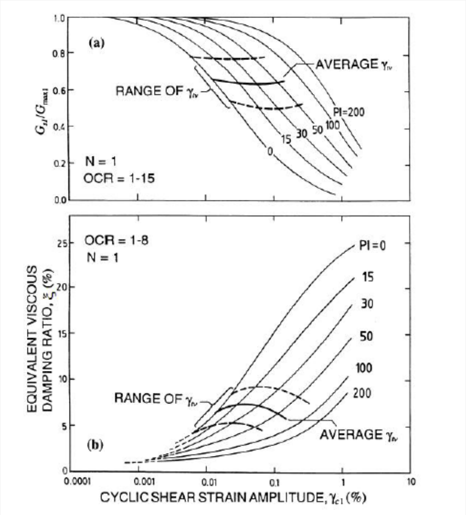
- Soil / rock constitutive models and input parameters
- Structural behaviour (steel / reinforced concrete) – linear and nonlinear
- Various forms of in-situ and laboratory testing required to determine input for dynamic analyses



Nonlinear concrete model (Lee and Fenves)



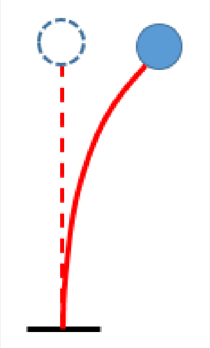
Seismic CPT to determine Vs

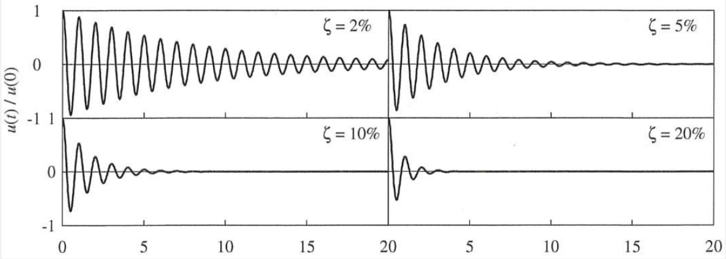


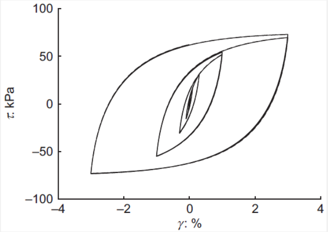
Dynamic soil curves (Gmax reduction and damping)

Other considerations: Damping

- Damping is the process by which free vibration steadily diminishes in amplitude.
- Two mechanisms
  - Spreading of energy (linear)
  - Dissipation of energy (nonlinear)
- "Types" of damping
  - Viscous damping (Rayleigh damping is one variation)
  - Hysteretic damping
  - Coulomb (or friction) damping
  - Radiation (or Geometric) damping







Damping in structures – Viscous damping

- "Impossible" to model all physical dissipation mechanisms in actual structures
- Instead, we use viscous damping to model the overall (global) damping in structure
- 5% damping often "blindly" specified for several types of structures (buildings, offshore platforms, dams, …)

Potential pitfalls with structural damping for SSI

- Damping measured in the field is the <u>total damping</u> in the system
- Thus, the amount of structural (viscous) damping must be reduced when SSI is explicitly modelled to avoid double-counting

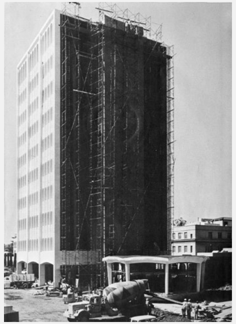


TABLE 11.1.1 NATURAL VIBRATION PERIODS AND MODAL DAMPING RATIOS OF MILLIKAN LIBRARY

Excitation	Roof Acceleration (g)	Fundamental Mode Period (sec)	Fundamental Mode Damping (%)	Second Mode Period (sec)	Second Mode Damping (%)
		North–South Direction			
Vibration generator	5×10^{-3} to 20×10^{-3}	0.51–0.53	1.2–1.8	a	a
Lytle Creek earthquake	0.05	0.52	2.9	0.12	1.0
San Fernando earthquake	0.312	0.62	6.4	0.13	4.7
		East–West Direction			
Vibration generator	3×10^{-3} to 17×10^{-3}	0.66–0.68	0.7–1.5	b	b
Lytle Creek earthquake	0.035	0.71	2.2	0.18	3.6
San Fernando earthquake	0.348	0.98	7.0	0.20	5.9

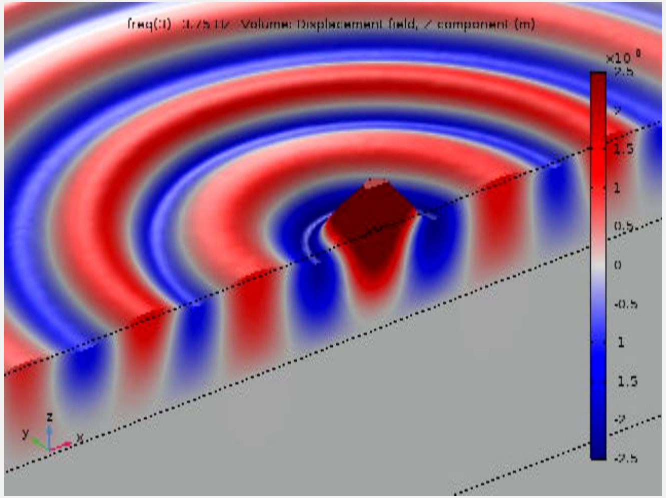
[a] Not measured.
[b] Data not reliable.

From Chopra (2012)

Radiation damping

- Energy loss due to waves generated by a source and propagated to the far distance.
- Exists even in a perfectly “undamped” soil or rock.
- Increases with frequency -> damping is low for long period structures but can be (very) high for high-frequency systems such as concrete dams and NPPs.

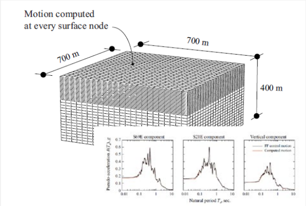
- **NB! Combination of homogeneous rock/soil models and high frequencies tend to result in unrealistically high damping values -> Most often codes have caps on maximum amount of damping allowable.**
- **NB2! Not possible to know total damping a-priori in a dynamic SSI model -> Need to do numerical calibrations.**



Dynamic SSI is complex – how can we ensure integrity of our models?

Should <u>verify</u> all major parts of model

- Seismic input and foundation-structure interaction
- "Basic" model aspects
  - Element types, mesh, damping model, etc.
  - Dynamic properties
- Nonlinear model aspects
  - Constitutive models, input properties, etc.



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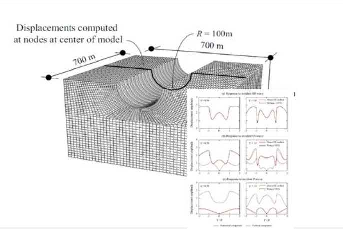

Semi-cylindrical canyon test

Model should be <u>validated</u> against field measurements when available

- E.g. natural frequencies and damping ratios
- If project-specific data is unavailable, validate against data from comparable structures
- Relatively easy and inexpensive to obtain calibration data from ambient vibration measurements

Verification and validation of the analysis model is an important part of any project report!

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- Summary

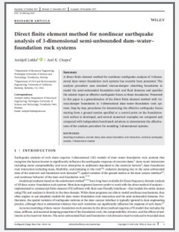
Summary

- The direct FE method is a time-domain analysis method suitable for linear or nonlinear analyses of soil/rock-structure systems
- Obtaining realistic free-field motion(s) is an important step in dynamic SSI analyses – usually based on PSHA and assumes vertically propagating waves
- Dynamic SSI analyses are substantially more complicated than static analyses – essential to verify and validate our models

More information

Løkke and Chopra (2017). "Direct finite element method for nonlinear analysis of semi-unbounded dam–water–foundation rock systems". *Earthquake Engineering & Structural Dynamics*, 46.8, 1267-1285. https://doi.org/10.1002/eqe.2855

- Develops analytical framework underlying the direct FE method
- Derives governing equations of motion for 2D dam-water-foundation systems
- Validates method for 2D gravity dam systems



Løkke and Chopra (2018). "Direct finite element method for nonlinear earthquake analysis of 3-dimensional semi-unbounded dam–water–foundation rock systems". *Earthquake Engineering & Structural Dynamics*, 47(5), 1309-1328. https://doi.org/10.1002/eqe.3019

- Generalizes the direct FE method to 3D systems
- Presents procedures to compute effective earthquake forces for 3D systems
- Validates method for 3D arch dam systems

Løkke and Chopra (2019). "Direct finite element method for nonlinear earthquake analysis of concrete dams – simplification, modeling, and practical application". *Earthquake Engineering & Structural Dynamics*, 48(7), 818-842. https://doi.org/10.1002/eqe.3150

- Presents and evaluates simplifications of the method to facilitate its practical implementation
- Addresses modeling of principal nonlinear mechanisms and calibration of damping values
- Demonstrates implementation of the direct FE method with a commercial FE software

Thank you for your attention!

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