Hybrid Simulation: Similitude

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Dimensional Analysis

- Qualitative understanding of physical processes
- Basic dimensions (of interest for dynamics of structures):
  - Length (L)
  - Force (F)
  - Time (T)
- Results in non-dimensional factors (Pi-factors) that relate basic dimensions to express the physics of the problem

Scale Factors

- Scale factor
- Length-force relation:
  - Dictated by preserving the scale of modulus of elasticity (stress)
- Gravity-time relation:
  - Gravity is the same
  - Effect of gravity may be important
- Sometimes, we can neglect effects of gravity loads on response
  - Preserve mass density

$$S = \frac{D_{prototype}}{D_{model}}$$

$$S_F = S_L^2; \quad S_E = 1$$

$$S_g = 1; \quad S_T = \sqrt{S_L}$$

$$S_\rho = 1; \quad S_T = S_L$$

Summary: Earthquake Testing

Table 2.11 Summary of Scale Factors for Earthquake Response of Structures

			Scale Factors		
(1)	(2)	Dimension (3)	True Replica Model (4)	Artificial Mass Simulation (5)	Gravity Forces Neglected Prototype Material (6)
Loading	Force, Q	F	$S_E S_l^2$	$S_E S_l^2$	S_l^2
	Pressure, q	FL^{-2}	S_E	S_E	1
	Acceleration, a	LT^{-2}	1	1	S_l^{-1}
	Gravitational acceleration, g	LT^{-2}	1	1	Neglected
	Velocity, v	LT^{-1}	$S_l^{1/2}$	$S_l^{1/2}$	1
	Time, t	T	$S_l^{1/2}$	$S_l^{1/2}$	S_l
Geometry	Linear dimension, l	L	S_l	S_l	S_l
	Displacement, δ	L	S_l	S_l	S_l
	Frequency, ω	T^{-1}	$S_l^{-1/2}$	$S_l^{-1/2}$	S_l^{-1}
Material properties	Modulus, E	FL^{-2}	S_E	S_E	1
	Stress, σ	FL^{-2}	S_E	S_E	1
	Strain, ε	—	1	1	1
	Poisson's ratio, ν	—	1	1	1
	Mass density, ρ	$FL^{-4}T^2$	S_E/S_l	[a]	1
	Energy, EN	FL	$S_E S_l^3$	$S_E S_l^3$	S_l^3

[a] $(g\rho l/E)_m = (g\rho l/E)_p$.

- Harris and Sabnis textbook

Constraints and Goals

- Constraints:
  - Laboratory size
  - Actuator force
  - Reaction capacity
  - Material (E and mass density)
- Goals:
  - Enable economical and realistic hybrid simulation of seismic response of structures
  - Usually, smaller is cheaper

Scaling in Hybrid Simulation

- Mass density is key
- Computer models do not have a problem
- Physical models:
  - Complete similitude (consistent scaling of gravity acceleration):

$$S_T = \sqrt{S_L}$$

  - Distorted model (still under gravity):

$$S_T = S_L$$

- Analysis by Kumar et.al.

Gravity Matters (Procedure 1)

- Preserve mass density
- Scale mass

$$S_{\gamma} = 1; \quad S_M = S_L^3$$

- May conduct test on:
  - Prototype
    - Obtain target displacement, scale it down, measure force, scale it up
  - Model
    - Scale excitation (amplitude and duration), solve, scale up the response
- Methods are equivalent

Gravity does not Matter (Procedure 2)

- Choose not to scale time $S_T = 1$
- Force and length factors remain
- May conduct tests on:
  - Prototype
  - Model:
    - If test is done on the model, the amplitude of ground motions must be scaled by length scale

A Comparison

Quantity (1)	Dimensions (2)	Procedure 1 (3)	Procedure 2 (4)
Length	L	(S)	(S)
Mass	M	(S^3)	S
Time	T	S	(1)
Stress	$ML^{-1}T^{-2}$	1	1
Velocity	LT^{-1}	1	S
Acceleration	LT^{-2}	$1/S$	S
Force	MLT^{-2}	(S^2)	(S^2)
Stiffness	MT^{-2}	S	S
Damping $(C = 2\xi\sqrt{KM})$	MT^{-1}	S^2	S
Natural frequency ω	T^{-1}	$1/S$	1

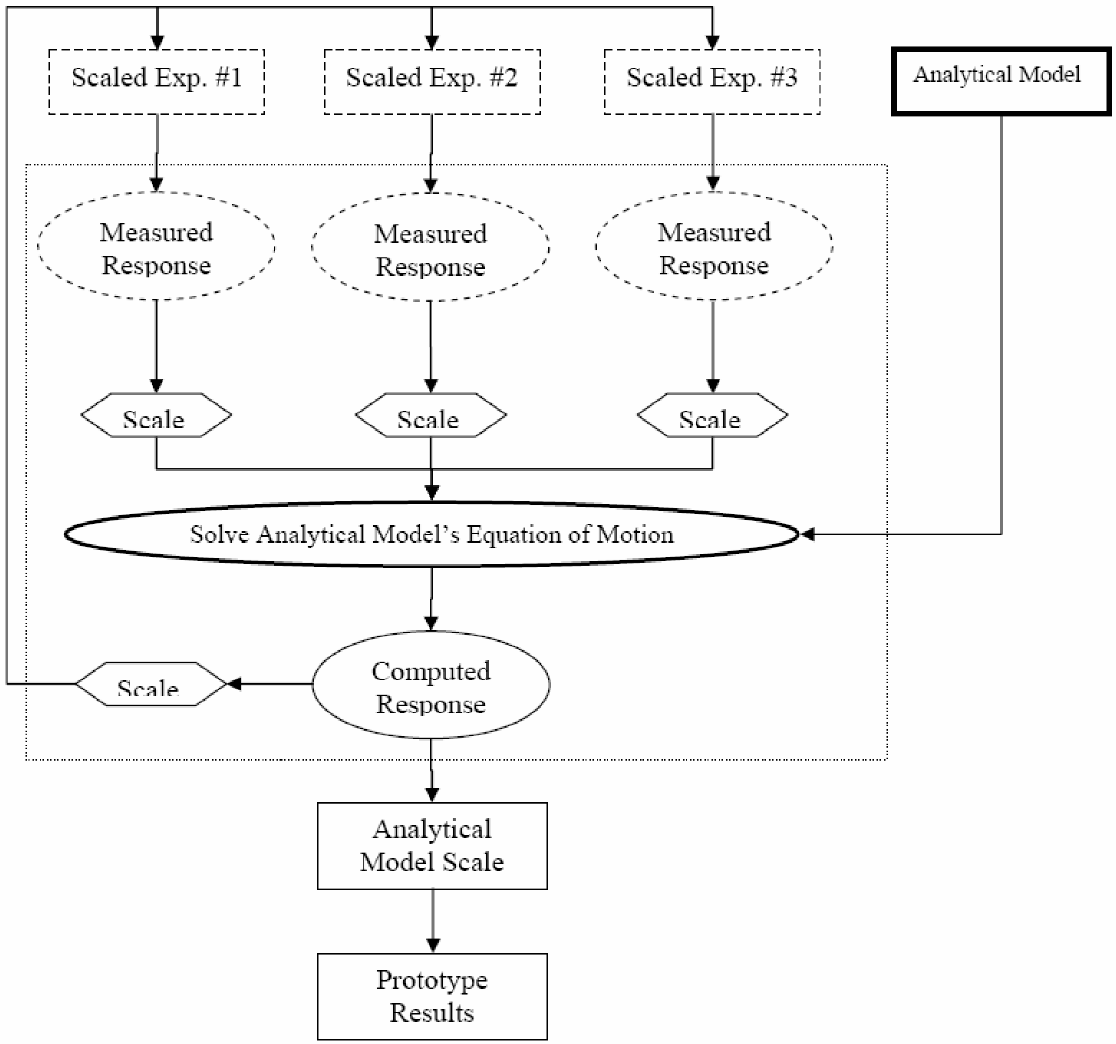
Note: Scale factor for quantity i; $S_i = i_p/i_m$; items in parentheses indicate specified factors.

- Kumar et.al.

Note on GM Scaling

- Many hybrid simulations conducted using Procedure 2 on the model are done without scaling the ground motion amplitude:
  - This is equivalent to using an S_L times stronger ground motion record
  - The structure may fail prematurely
  - The response may be highly non-linear

Similitude and Substructures

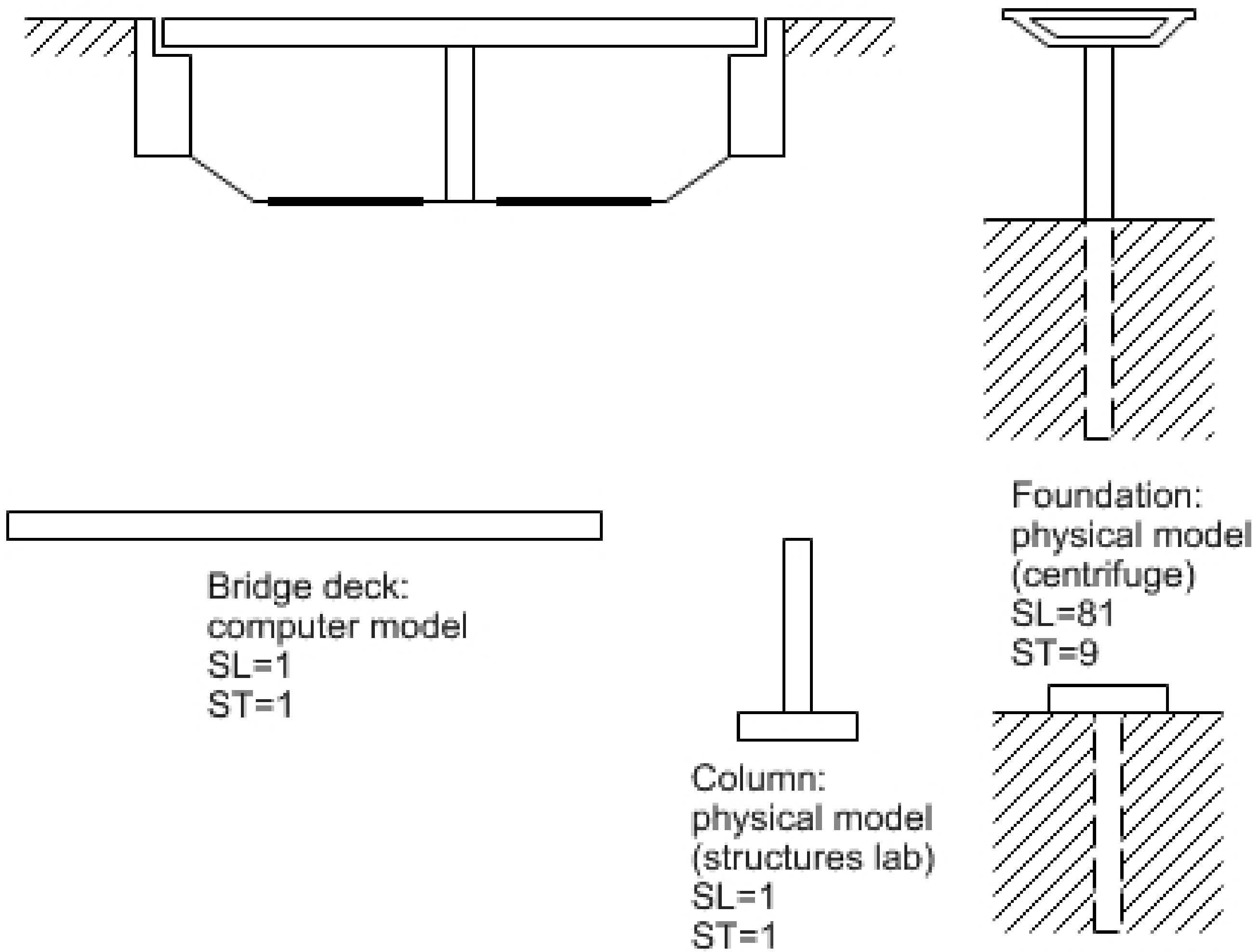


- Scaling to measured response and computed response
- Scale for substructures need not be the same!

Similitude and SubStructures

- Scaling must be consistent:
  - It is not necessary that the sub-structures have the same scale
  - It is, however, important that the their state data is correctly scaled wrt. the integrator scale
- Errors scale, too!
  - instruments have fixed error and sensitivity, thus it pays to use as large-scale physical models as possible

Example: Bridge SSI



Thank you!

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