Seismic Response of Towers (& Spires)

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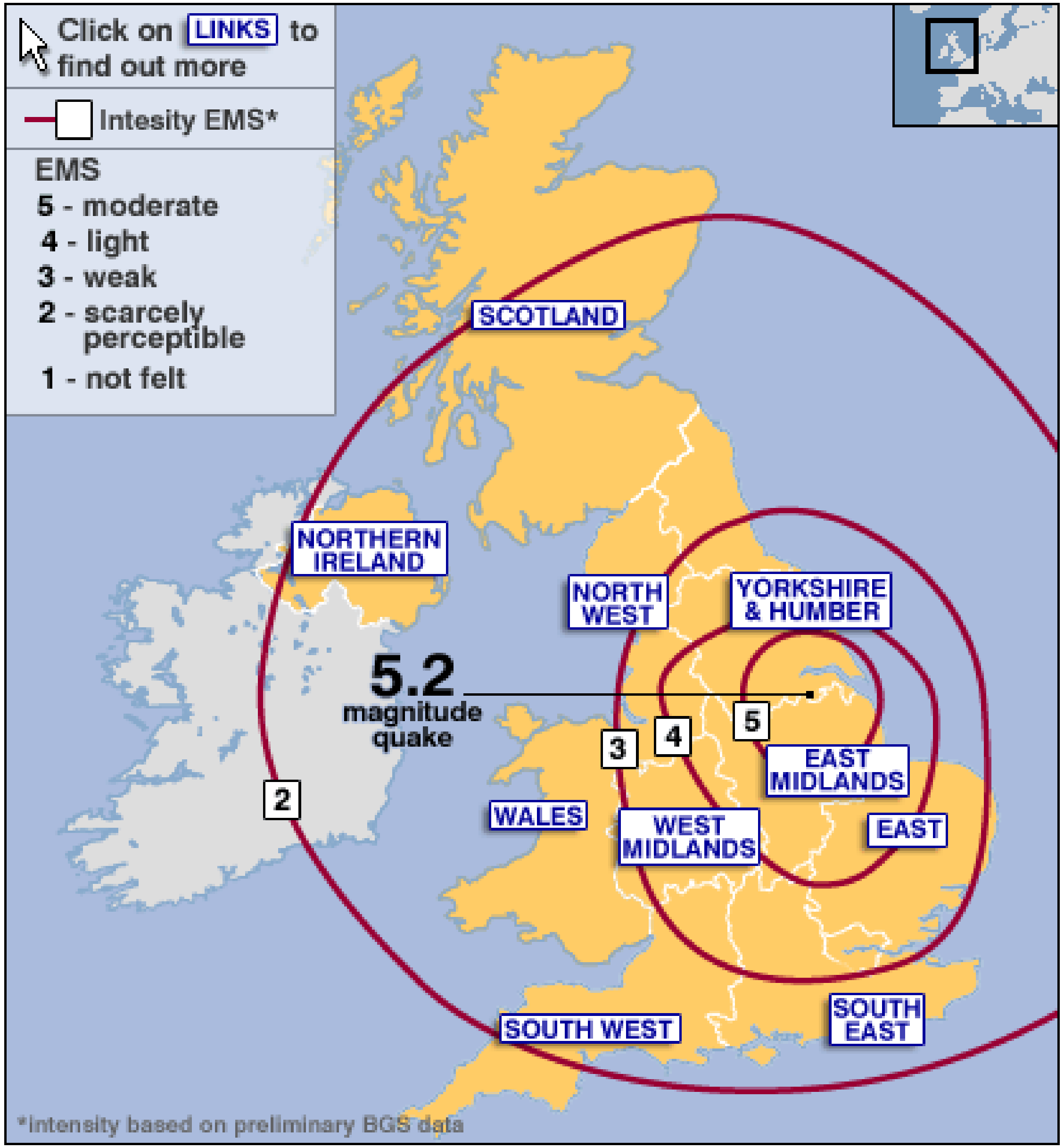
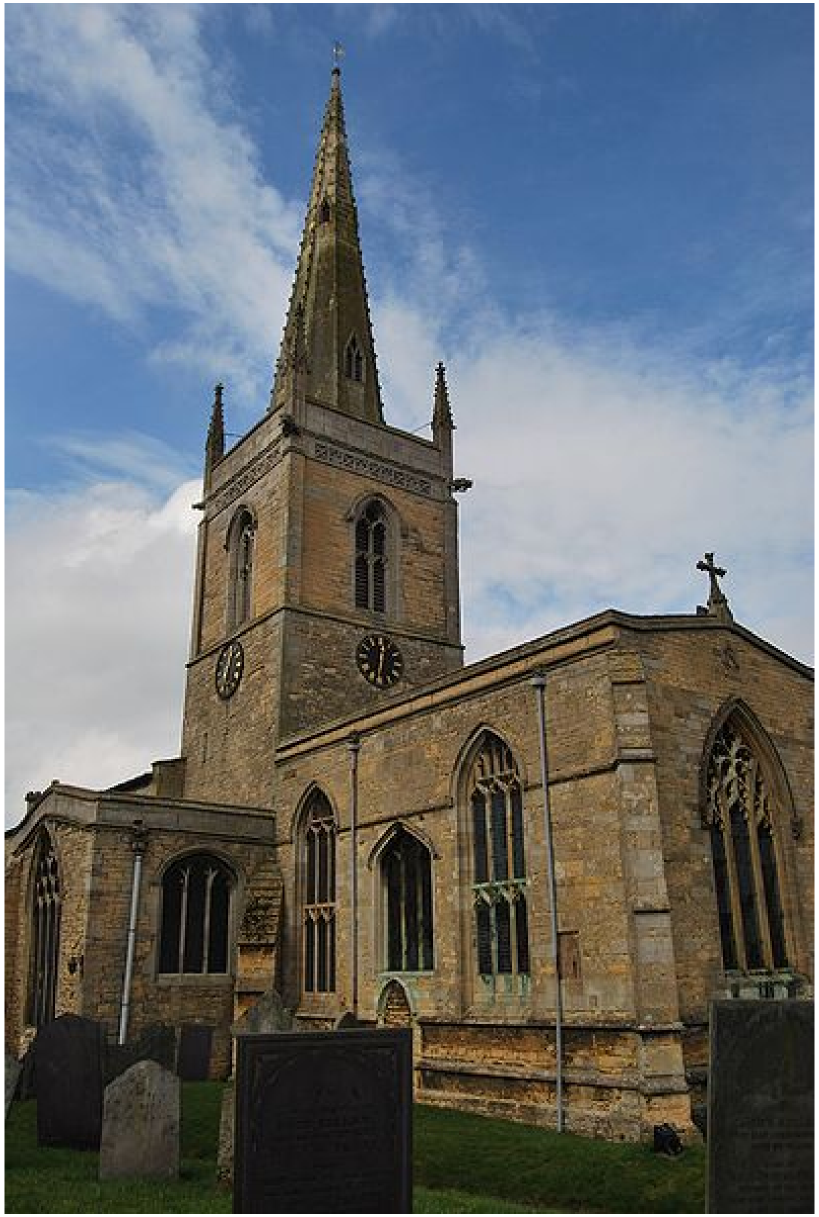
UNIVERSITY OF CAMBRIDGE


2011

Lincolnshire Earthquake, UK (2009)





Dharahara Tower, Kathmandu, Nepal (2015)


What drives collapse?

1. Elastic resonance?

2. Direct overturning

3. Vibration / walk apart / dis-integration

Important considerations for towers

Global geometry:

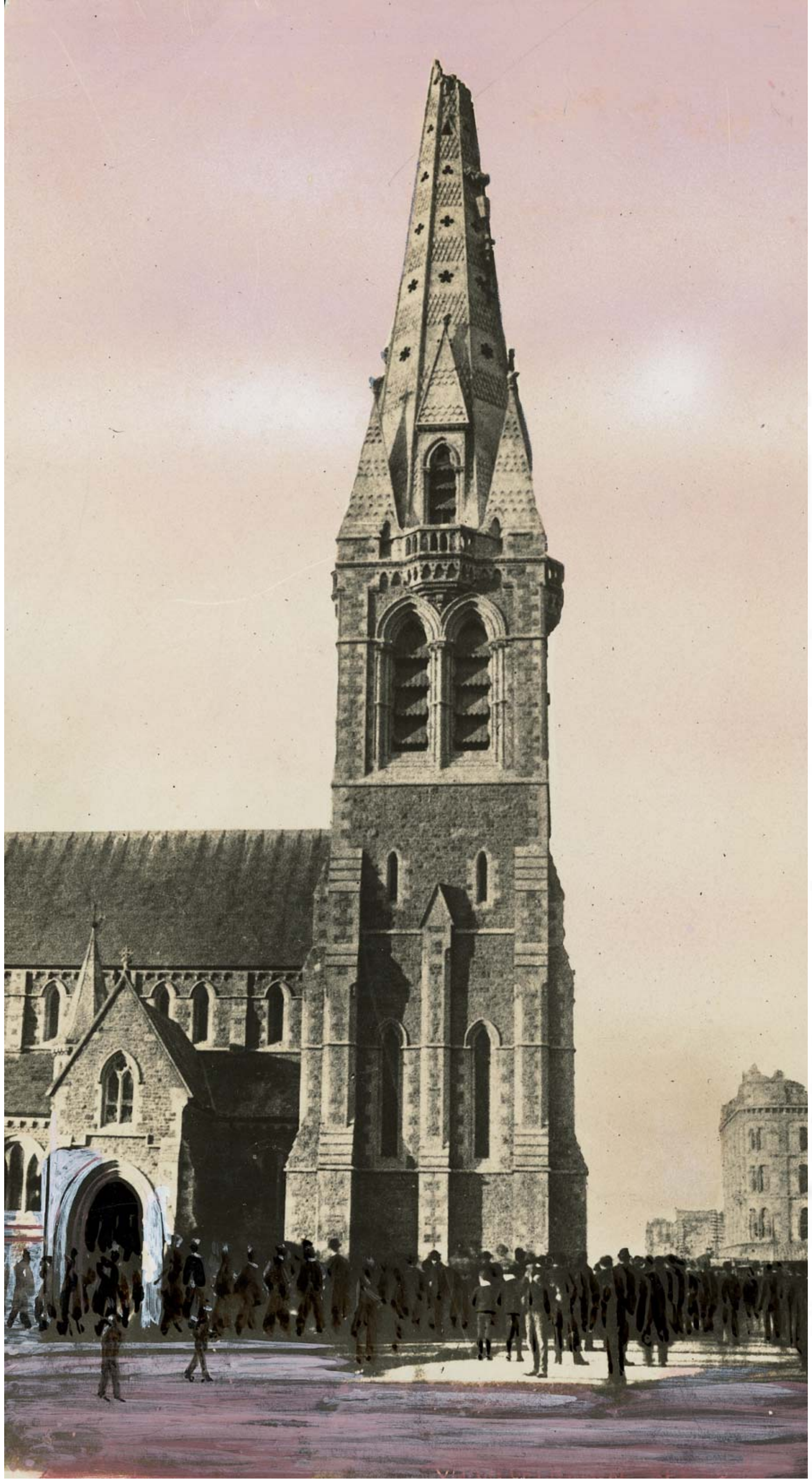
- Slenderness
- Size/scale

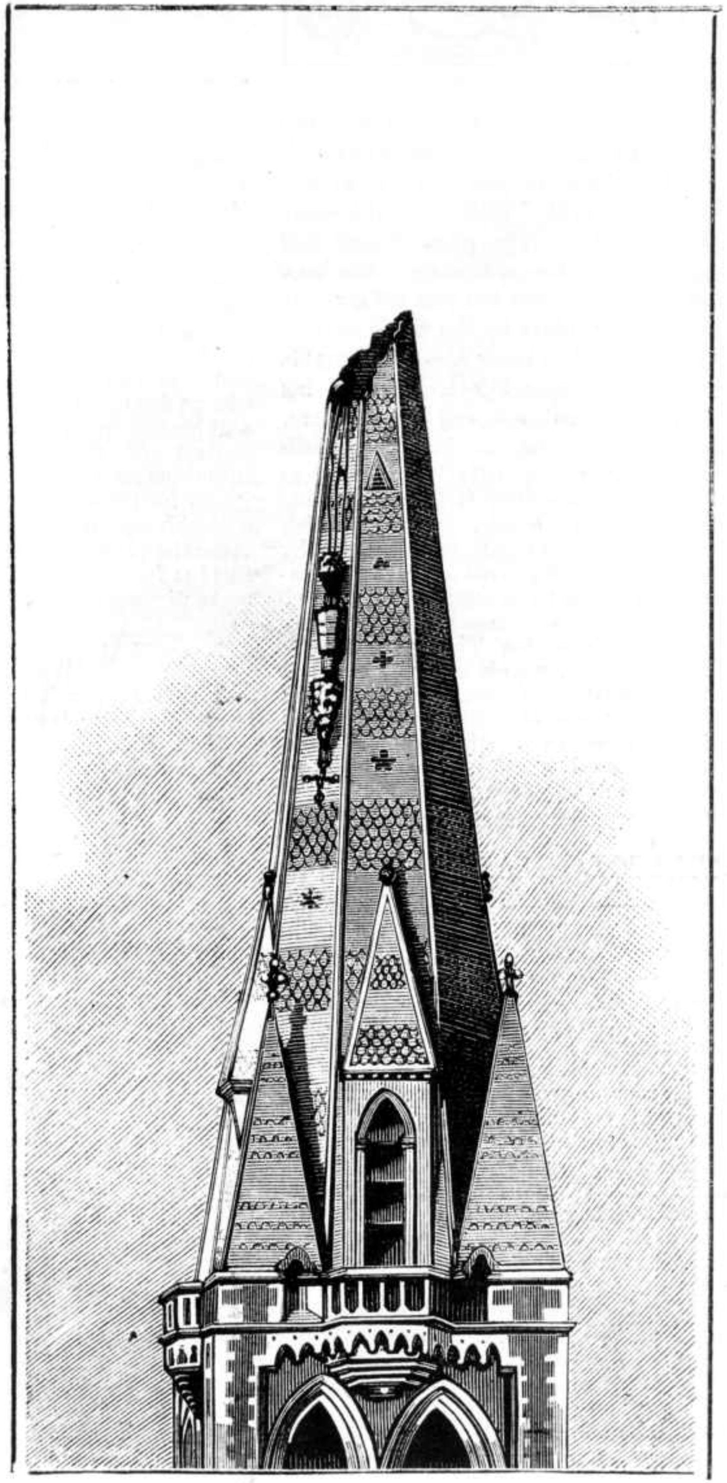
Details:

- Openings (particularly bell towers)
- Quality of construction
- Potential connection to (stiff) church?

Case Study #1: Christchurch Cathedral


1888





CHRISTCHURCH CATHEDRAL SPIRE
AFTER THE EARTHQUAKE.

1901

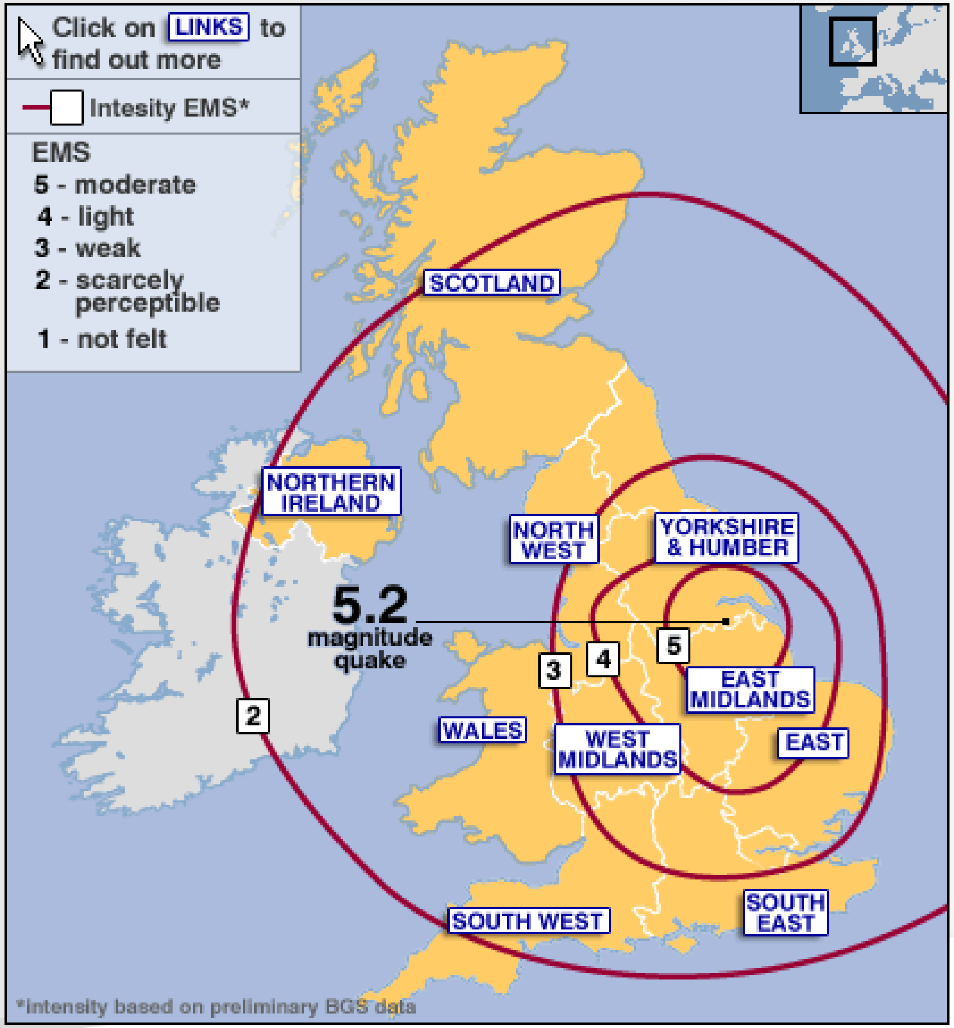

2011

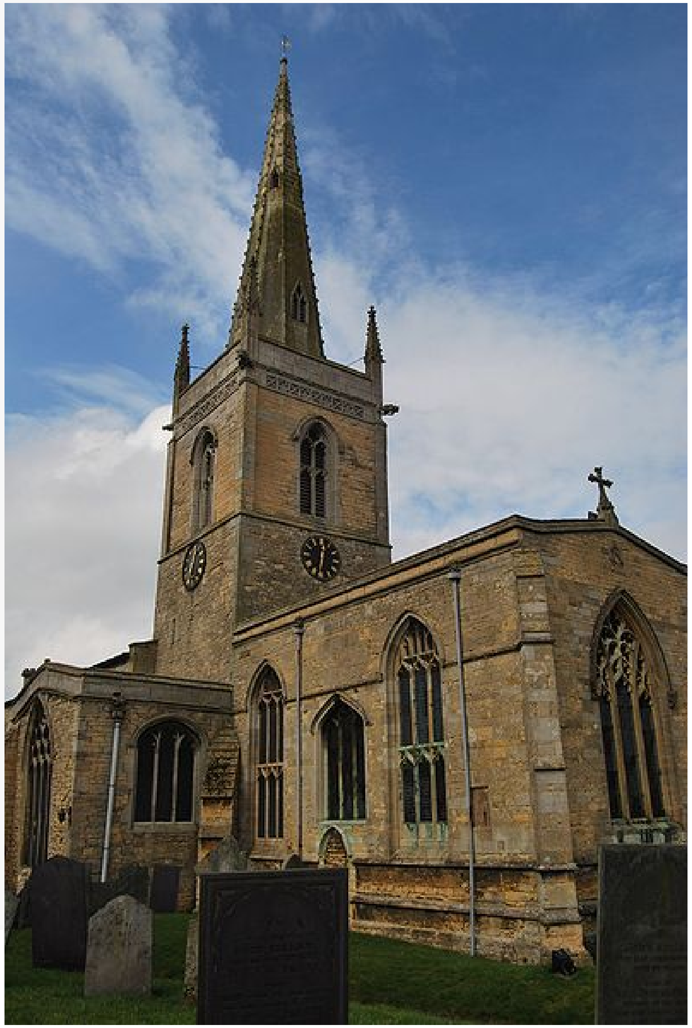
Relation to Philippines

- How to properly reconstruct?
  - maintain heritage
  - ensure seismic safety

Case Study #2: Lincolnshire, UK

Lincolnshire Earthquake, 2009





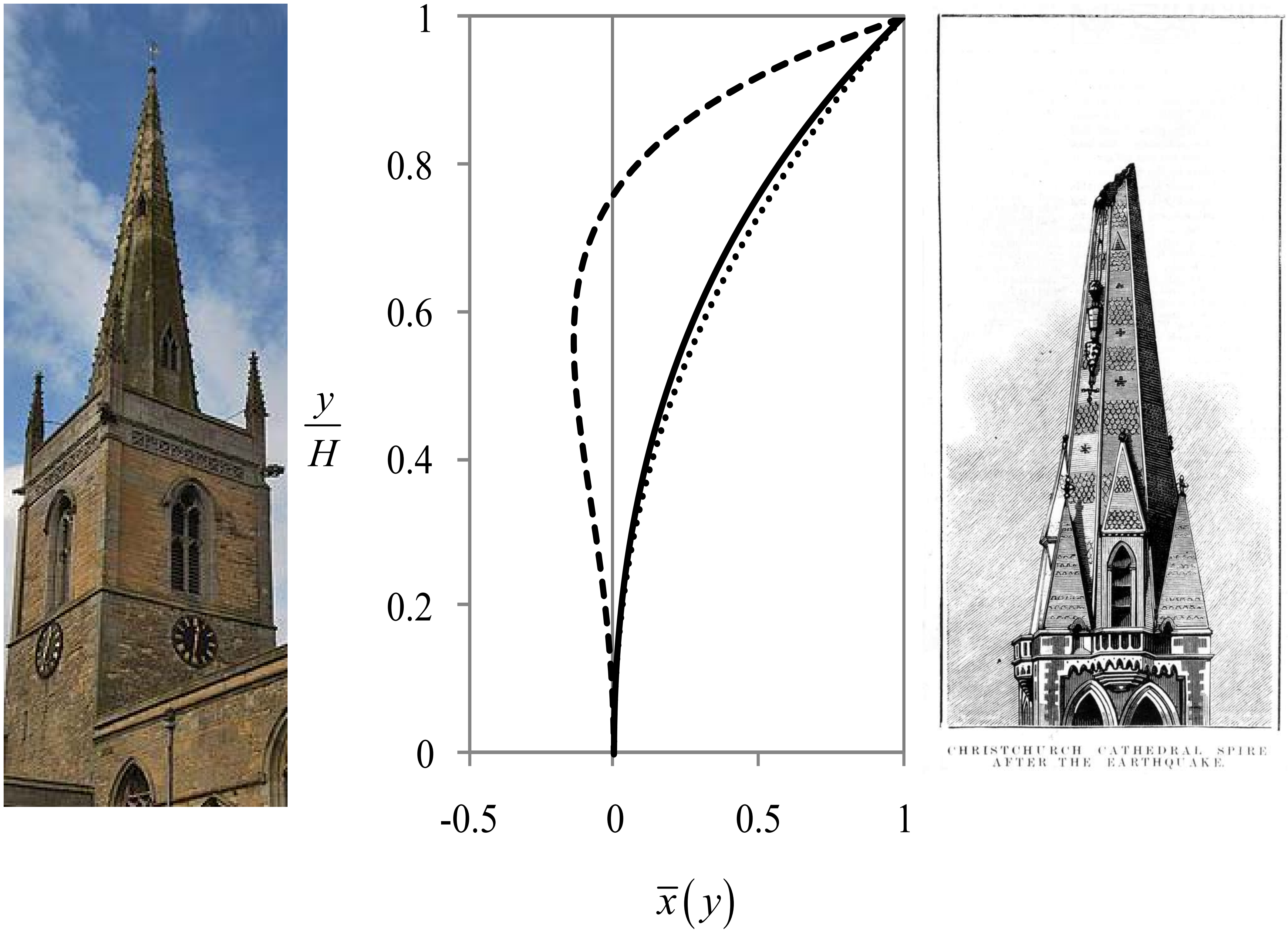
Stone Masonry Spire, Waltham on the Wolds, UK

What drives collapse?

1. Elastic resonance?

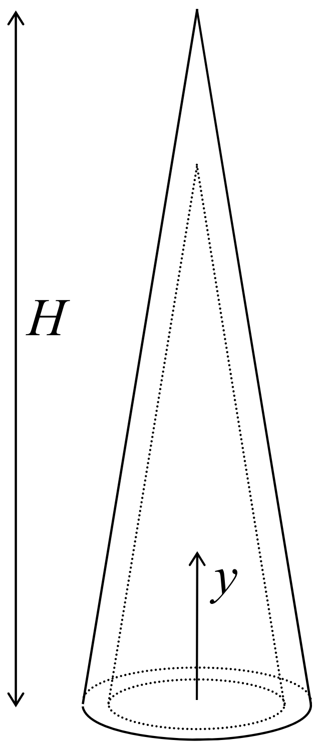
2. Direct overturning

3. Vibration / walk apart / dis-integration



1
0.8
0.6
0.4
0.2
0
y/H
-0.5
0
0.5
1
x̄(y)
CHRISTCHURCH CATHEDRAL SPIRE
AFTER THE EARTHQUAKE.

Analytical Elastic Analysis



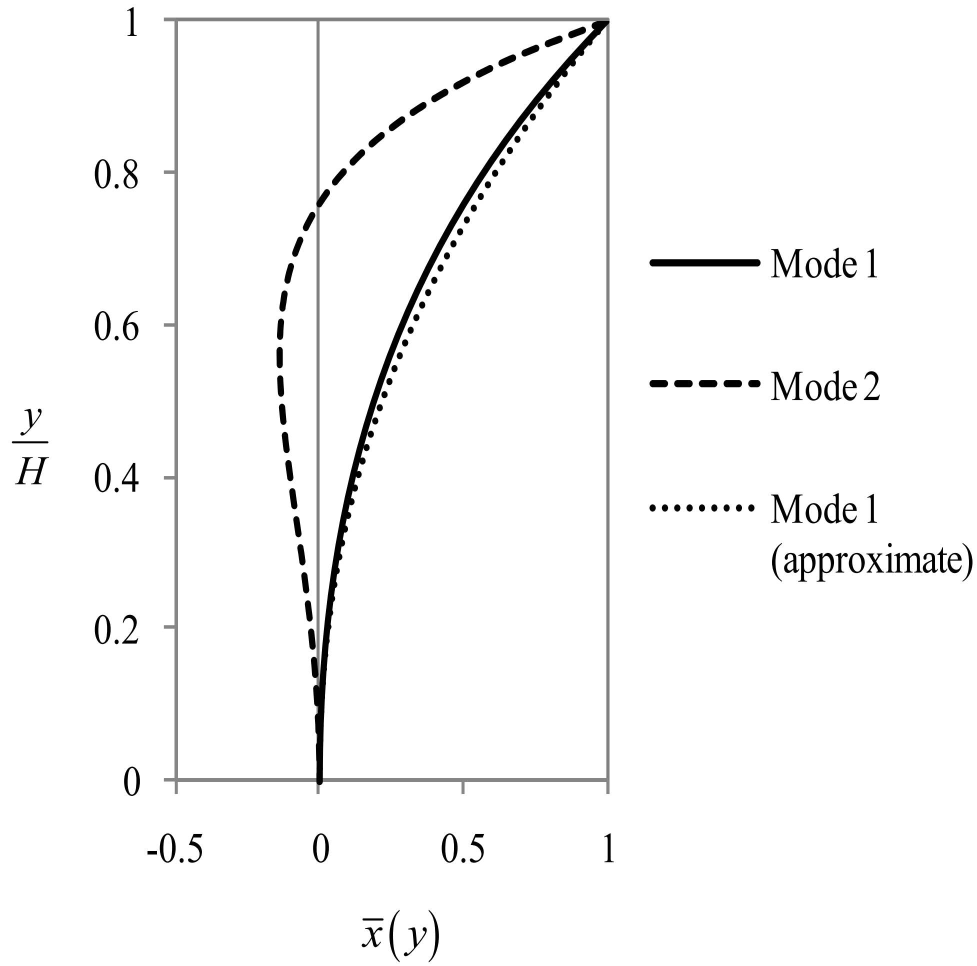
- Euler-Bernoulli Beam

$$m(y) = \left(1 - \frac{y}{H}\right) m_b$$

$$EI(y) = \left(1 - \frac{y}{H}\right)^3 EI_b$$

- Mode shape

$$\bar{x}(y) = \left(\frac{y}{H}\right)^k$$



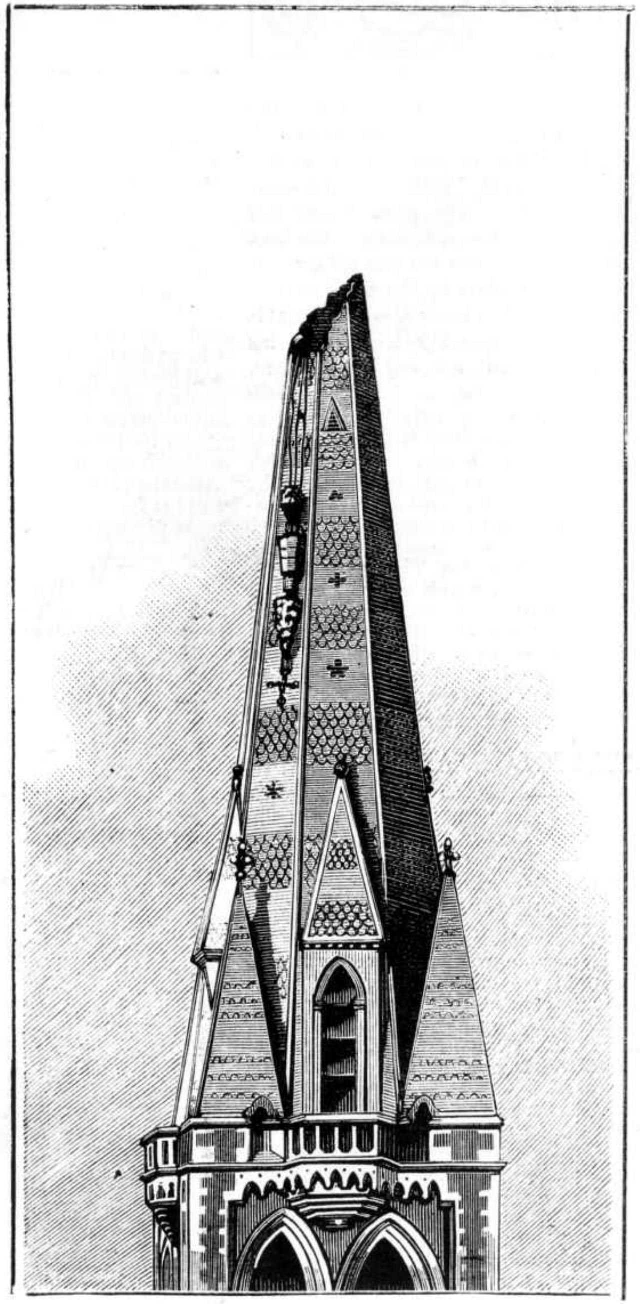
What drives collapse?

1. Elastic resonance?
   - Amplifies response
   - More important for slender structures
2. Direct overturning

3. Vibration / walk apart / dis-integration

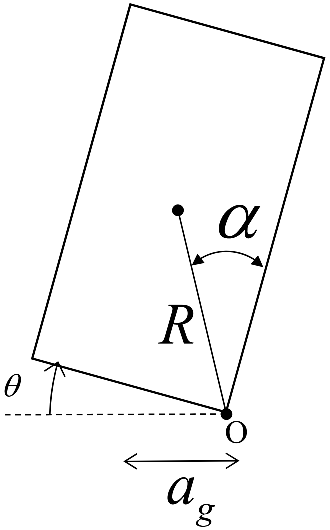
Lincolnshire, UK:

Chrischurch, NZ:

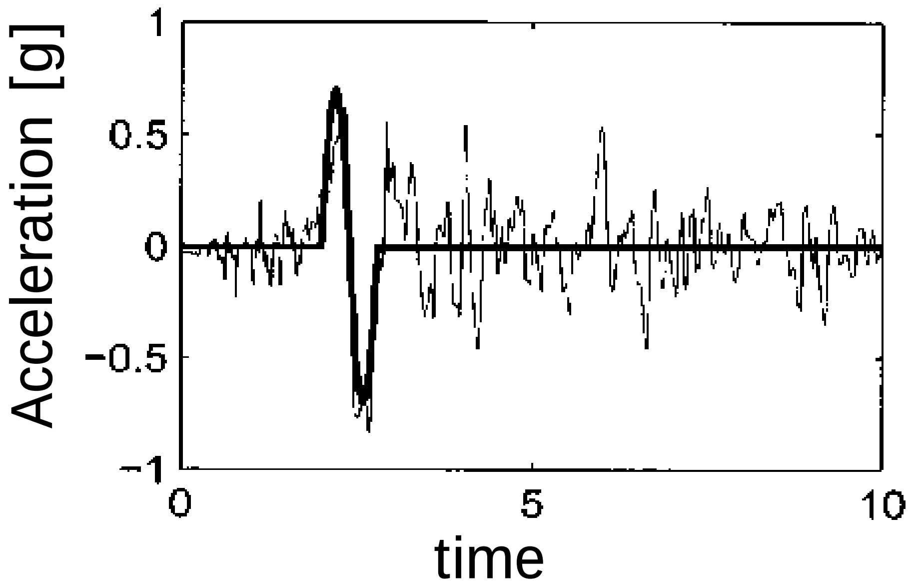


CHRISTCHURCH CATHEDRAL SPIRE AFTER THE EARTHQUAKE.

Vulnerability to direct overturning

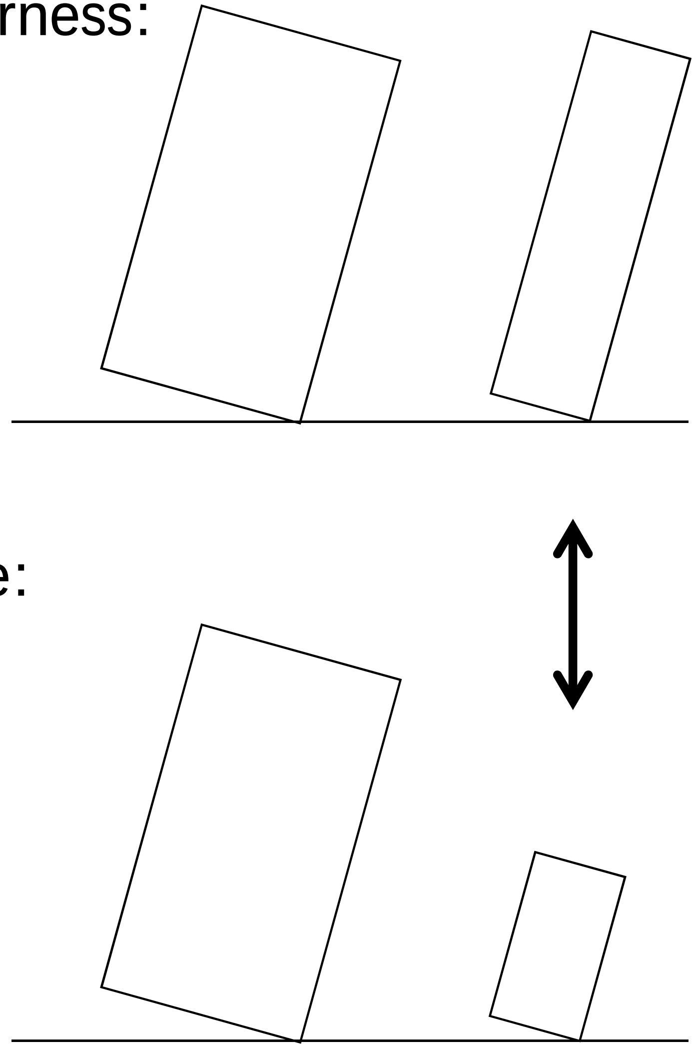


$$a_{g,limit} = \tan\alpha$$

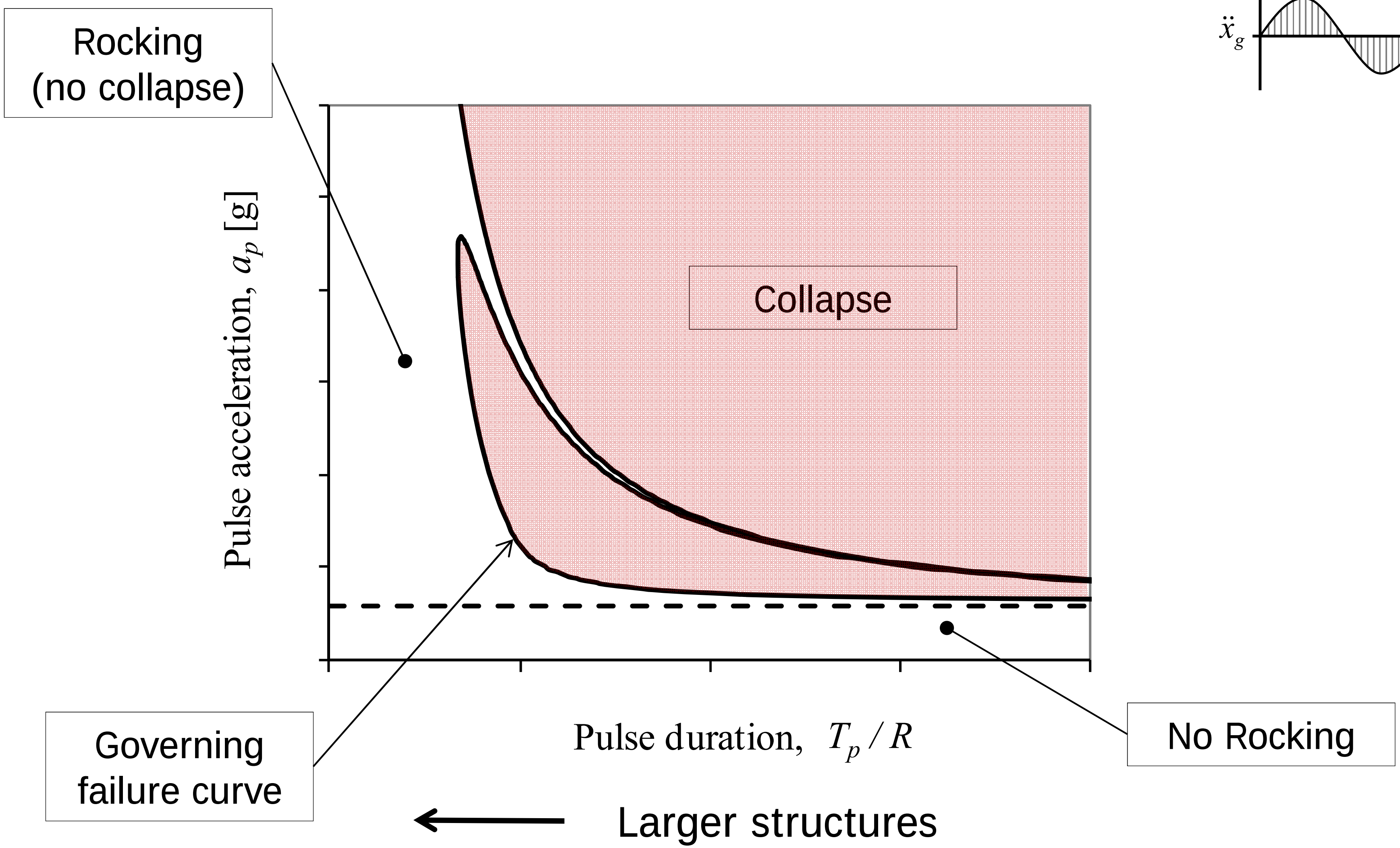


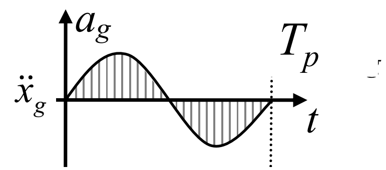
Slenderness:

Scale:



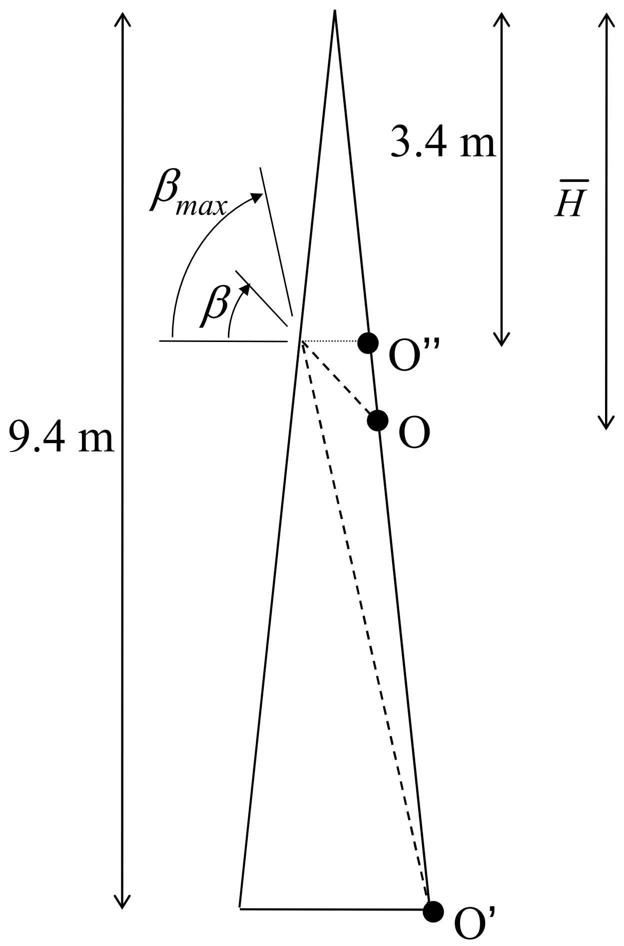
Rocking Block: Impulse Response





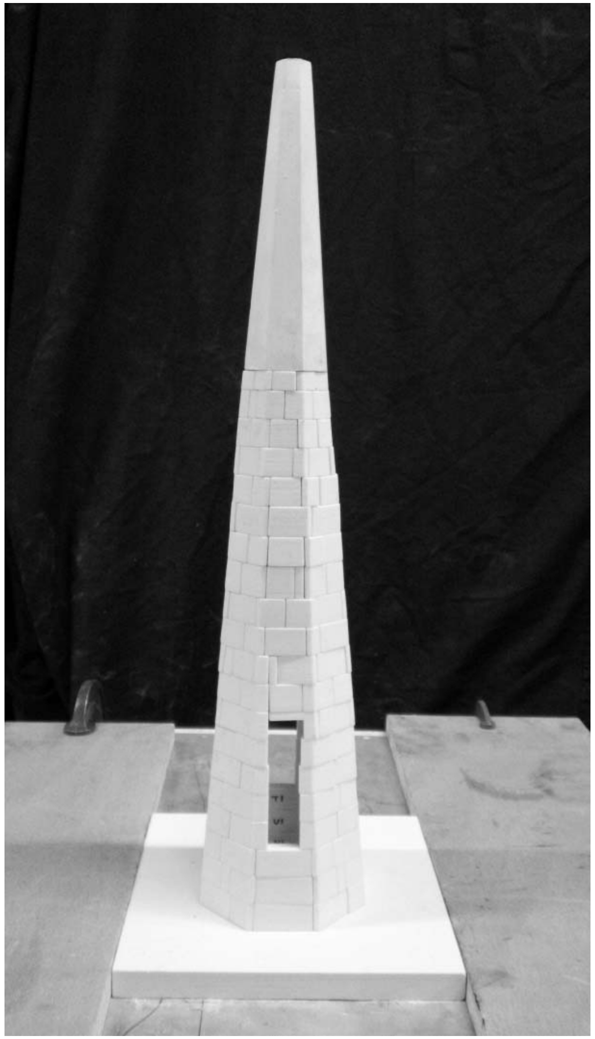
Stone Spire, Lincolnshire

Analytical



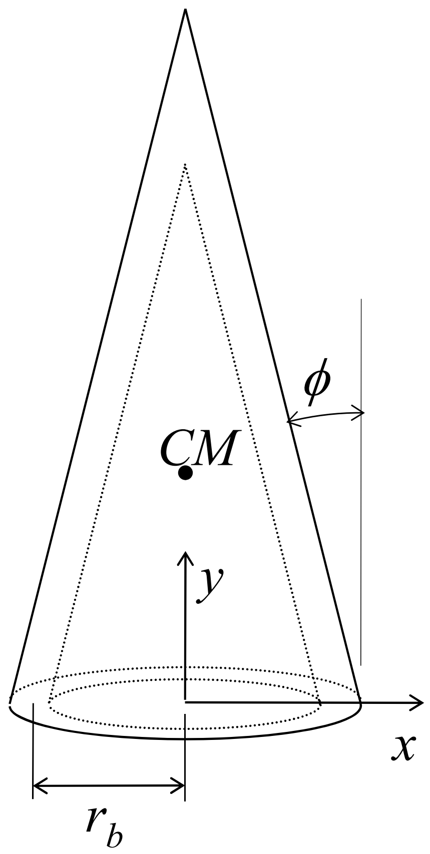
DEM

Physical

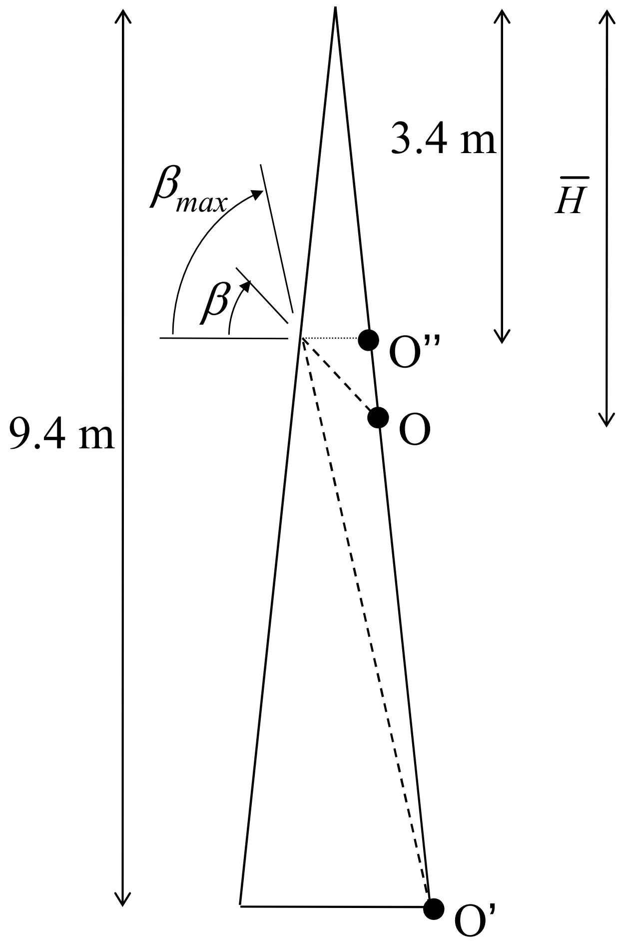


Hand Calculation

Geometry:



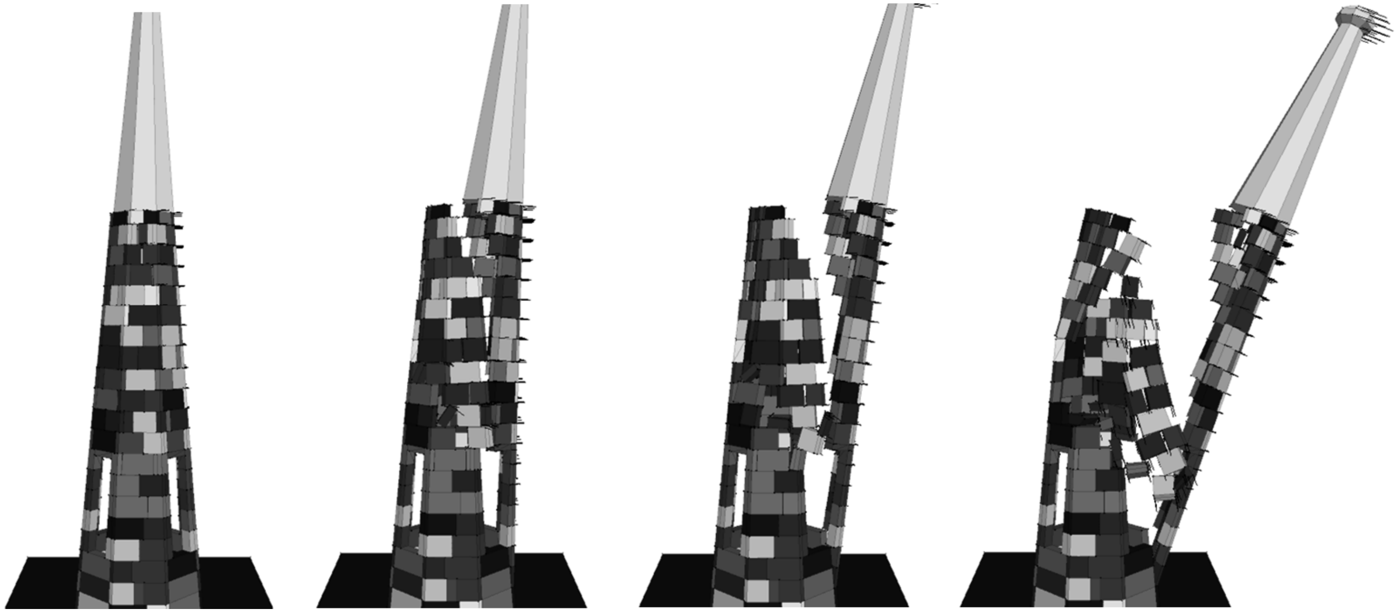
Failure mechanism:



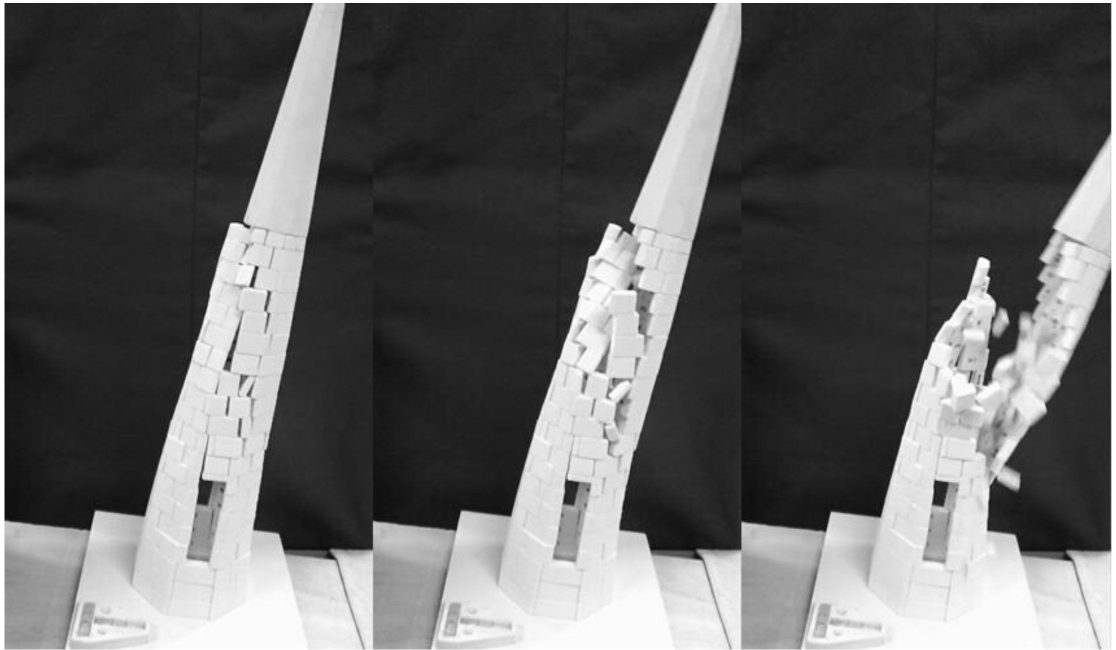
a_g = 0.19g
(perfect hollow cone)

Tilt Test

- DEM:
  a_g = 0.17g

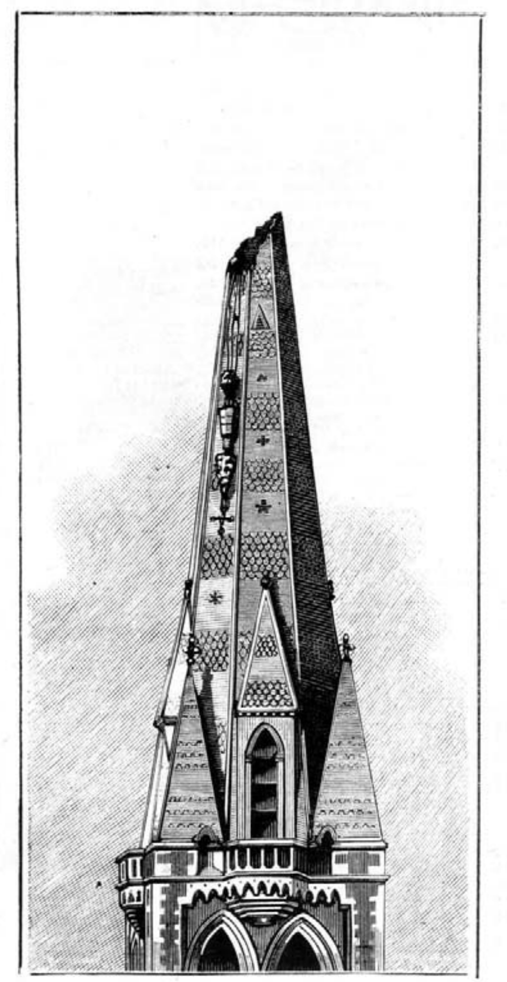


- Physical:
  a_g = 0.16g

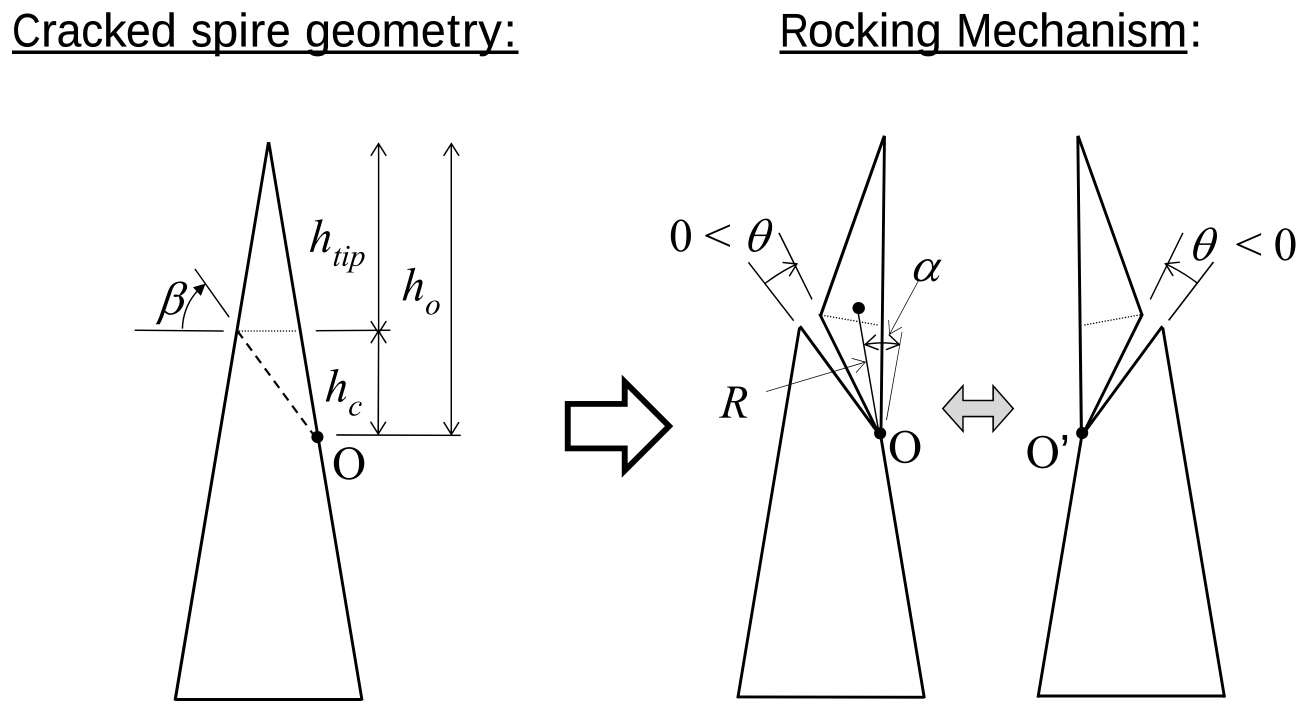


(Analytical: a_g = 0.19g)

Overturning – Include inertia

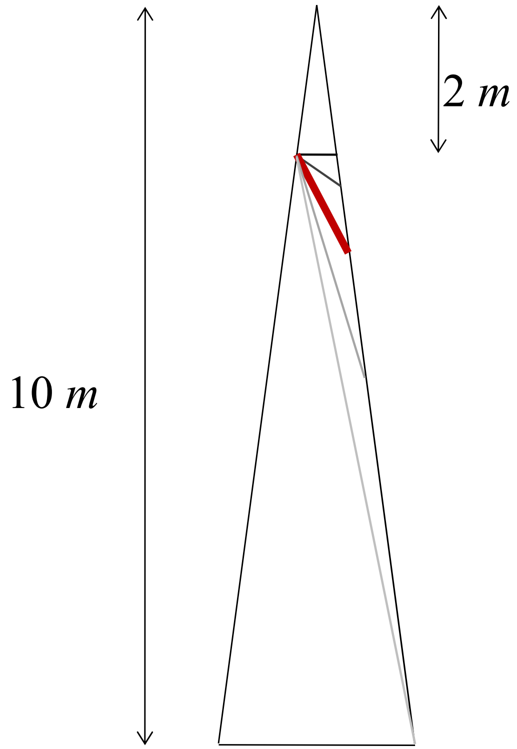


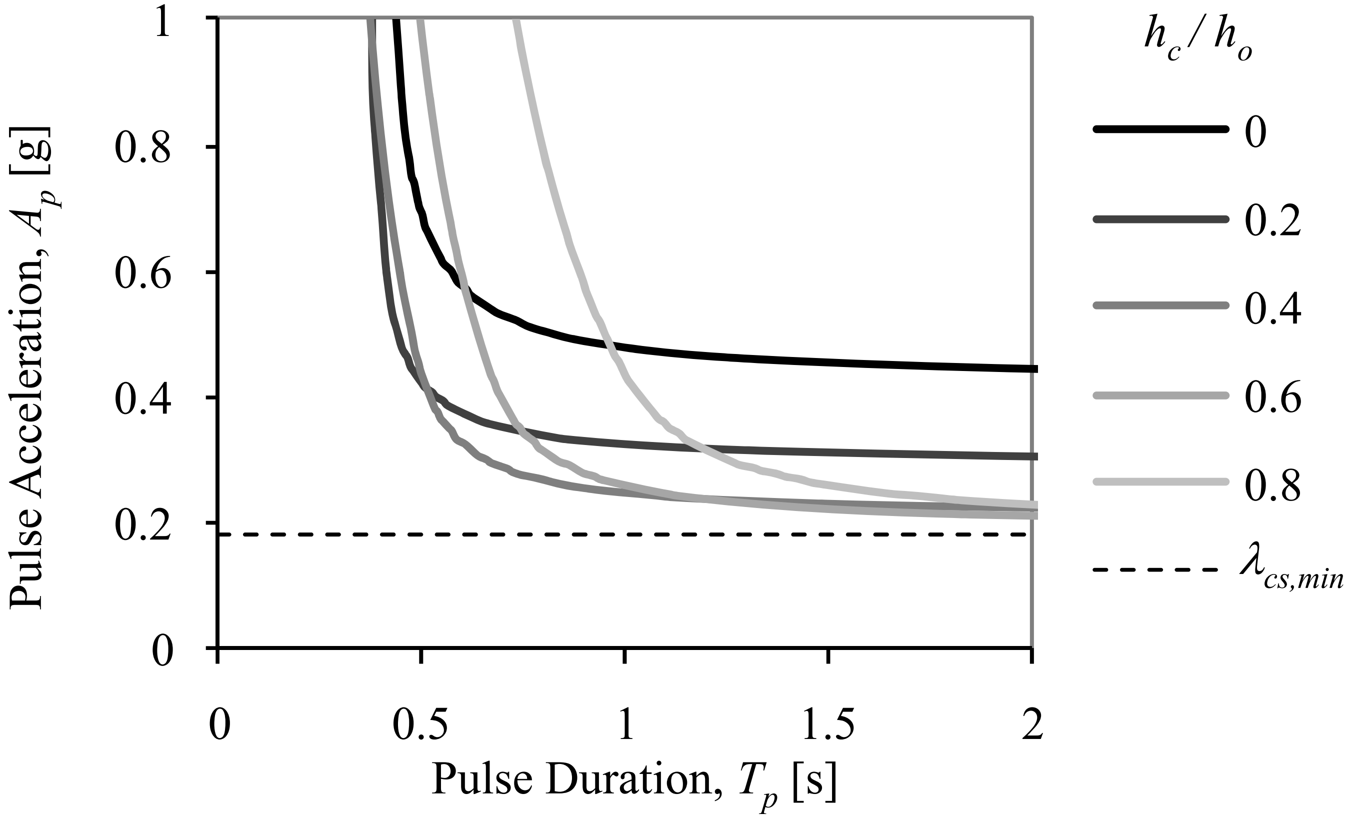
CHRISTCHURCH CATHEDRAL SPIRE AFTER THE EARTHQUAKE.



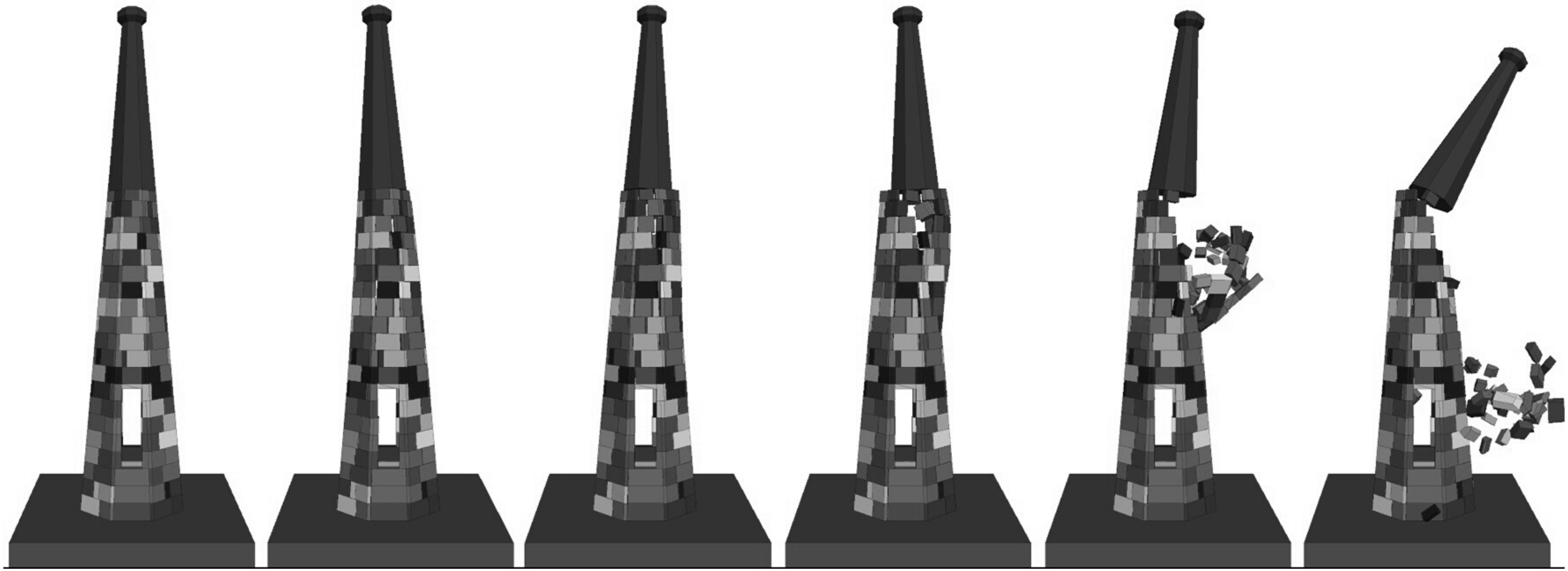
DeJong (2012). *Engineering Structures*, **40**, 556-565

Spire mechanisms



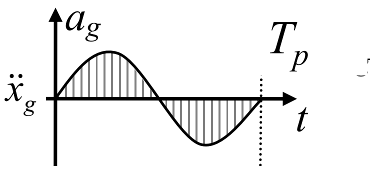


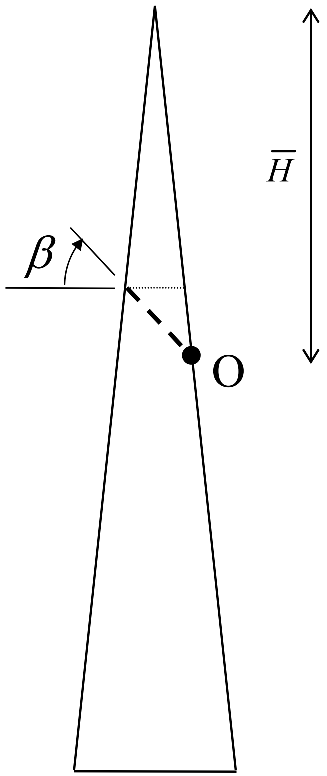
DEM - Impulse Rocking Response

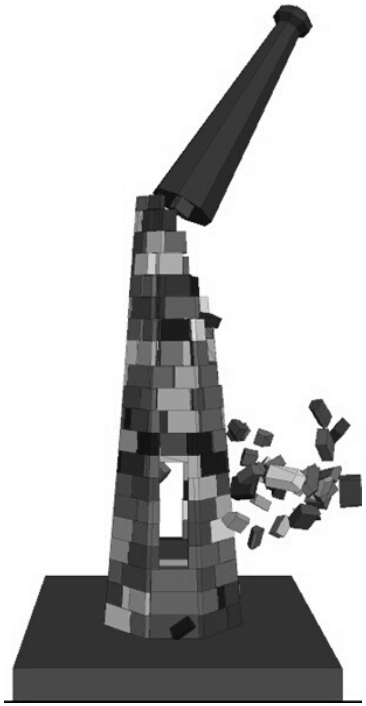


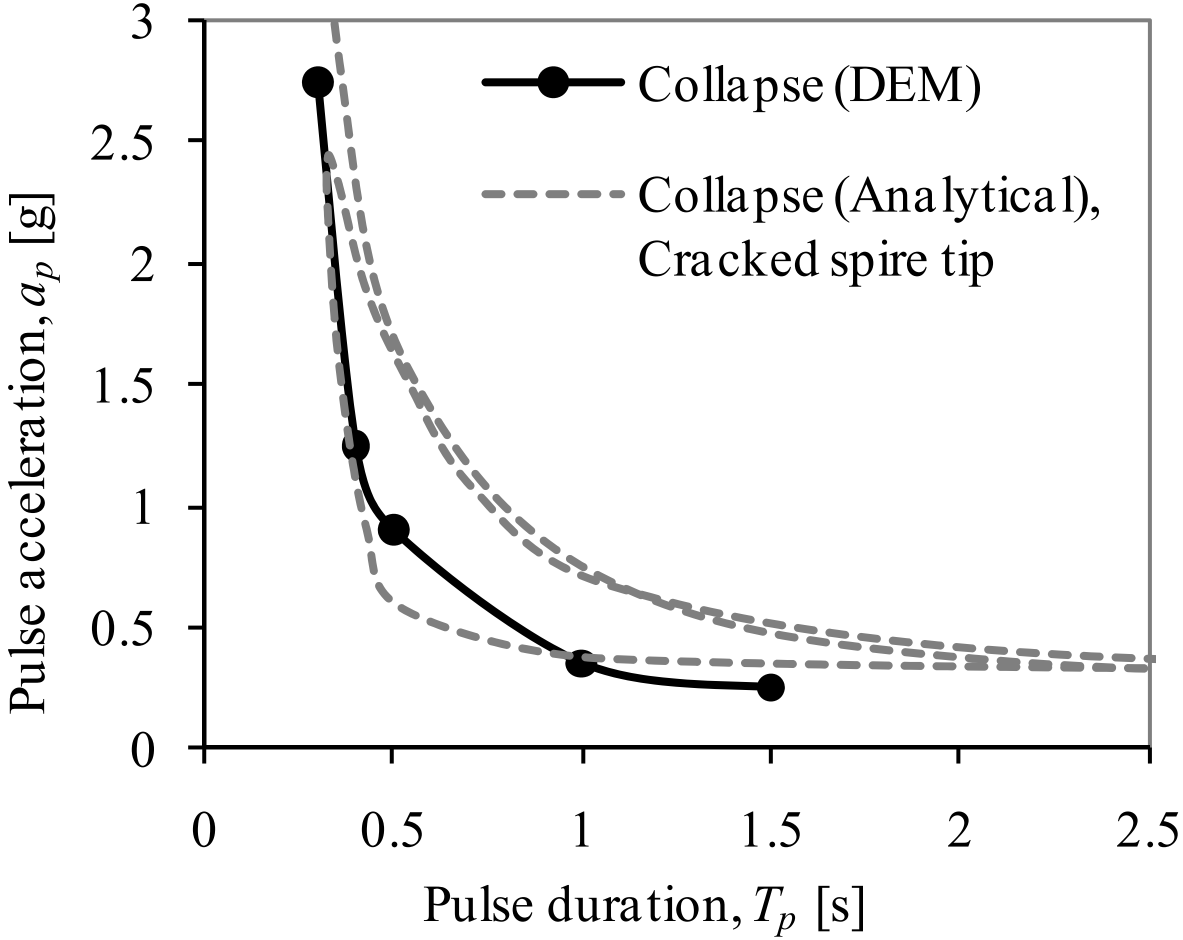
DeJong, Vibert (2012). *Engineering Structures*, **40**, 566-574

Impulse Response Comparison

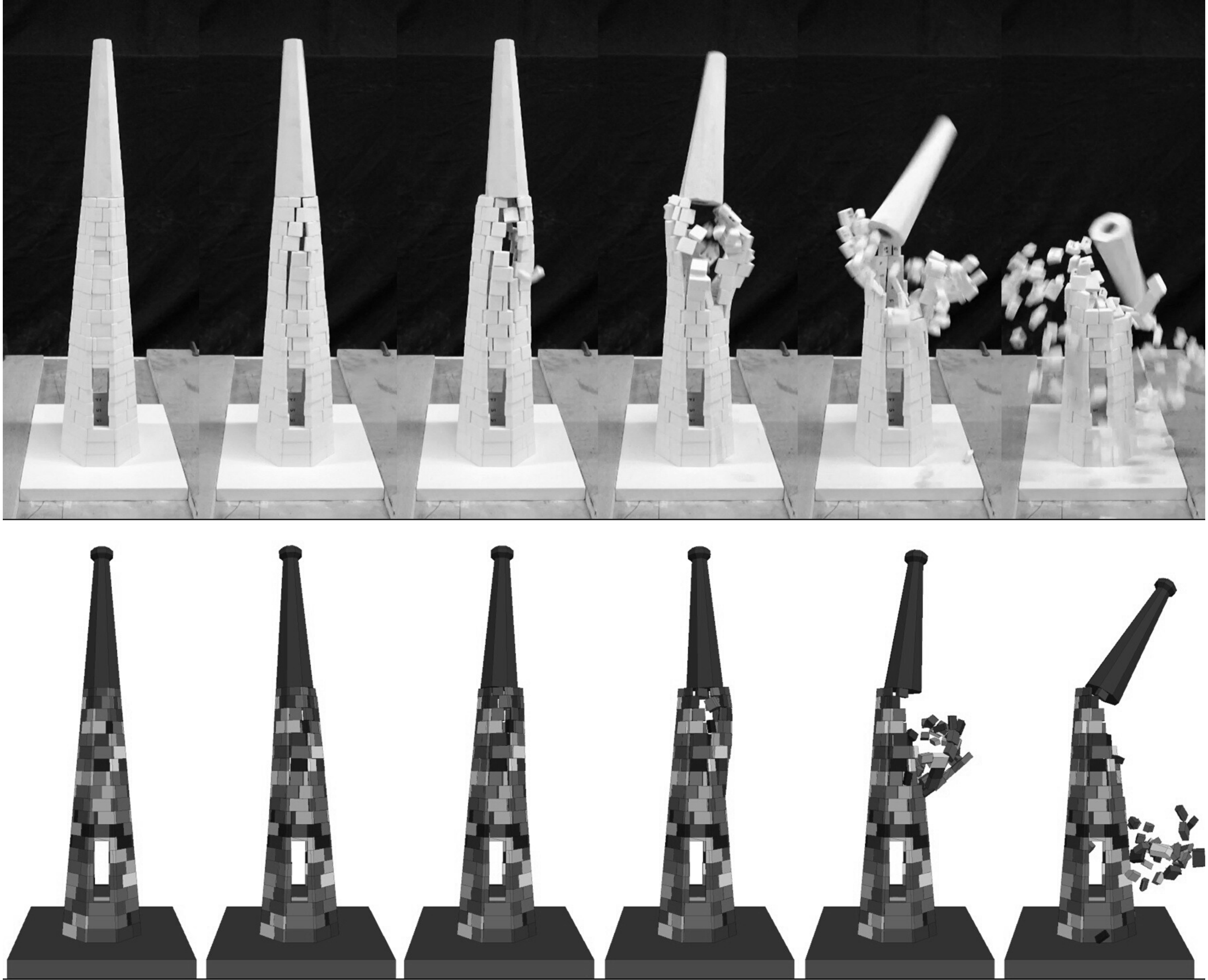








DeJong, Vibert (2012). *Engineering Structures*, **40**, 566-574



Direct overturning comments

- Slender = more vulnerable
- Smaller = more vulnerable

- PGA determines rocking initiation
- Length pulse (with respect to scale) causes larger maximum rotation

Direct overturning comments

- Another way to include effective “period” of earthquake (Italian building code)
  - Use design elastic response spectra to approximate the effect of “period” of the earthquake to better predict collapse

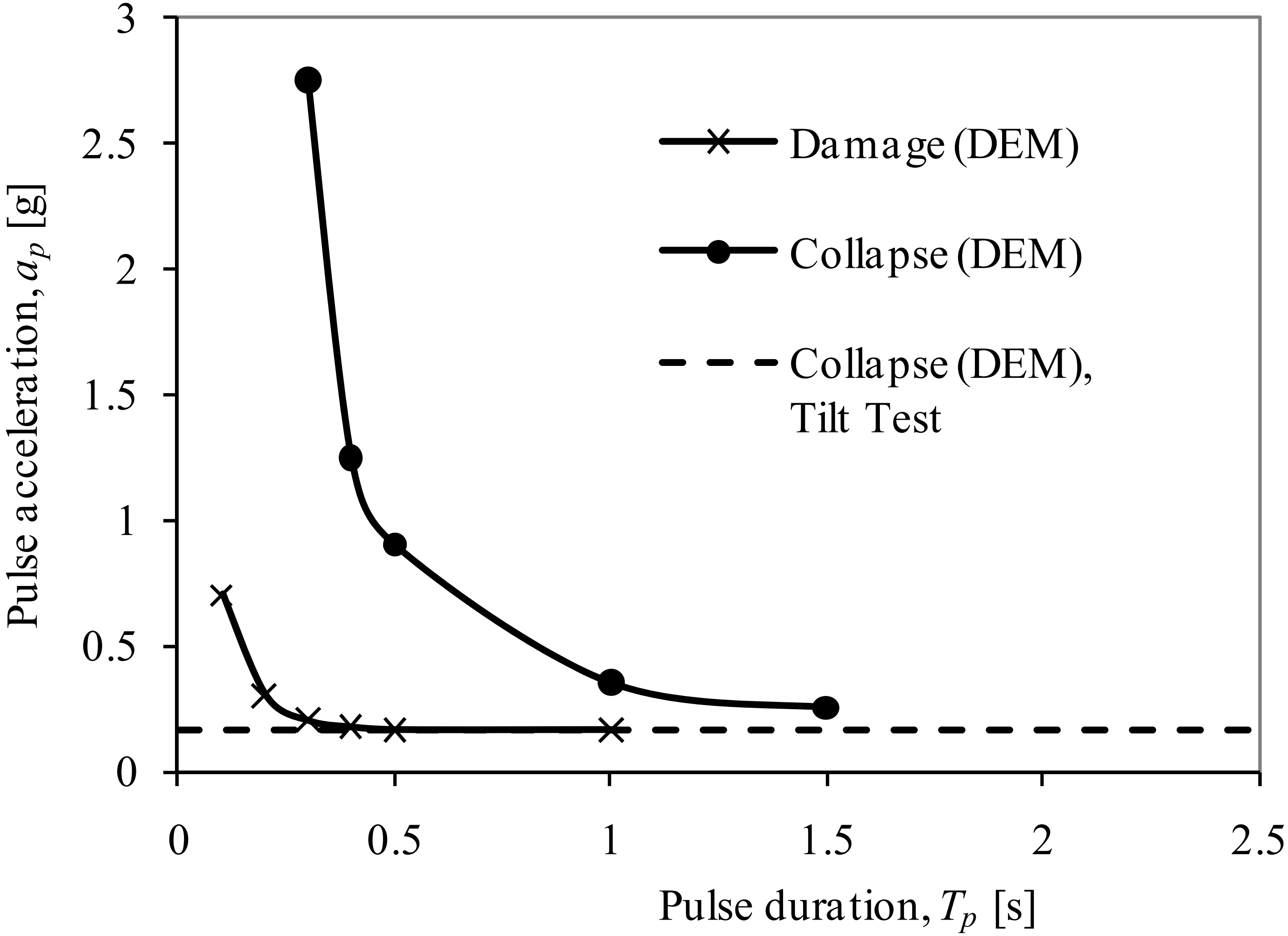
What drives collapse?

1. Elastic resonance?

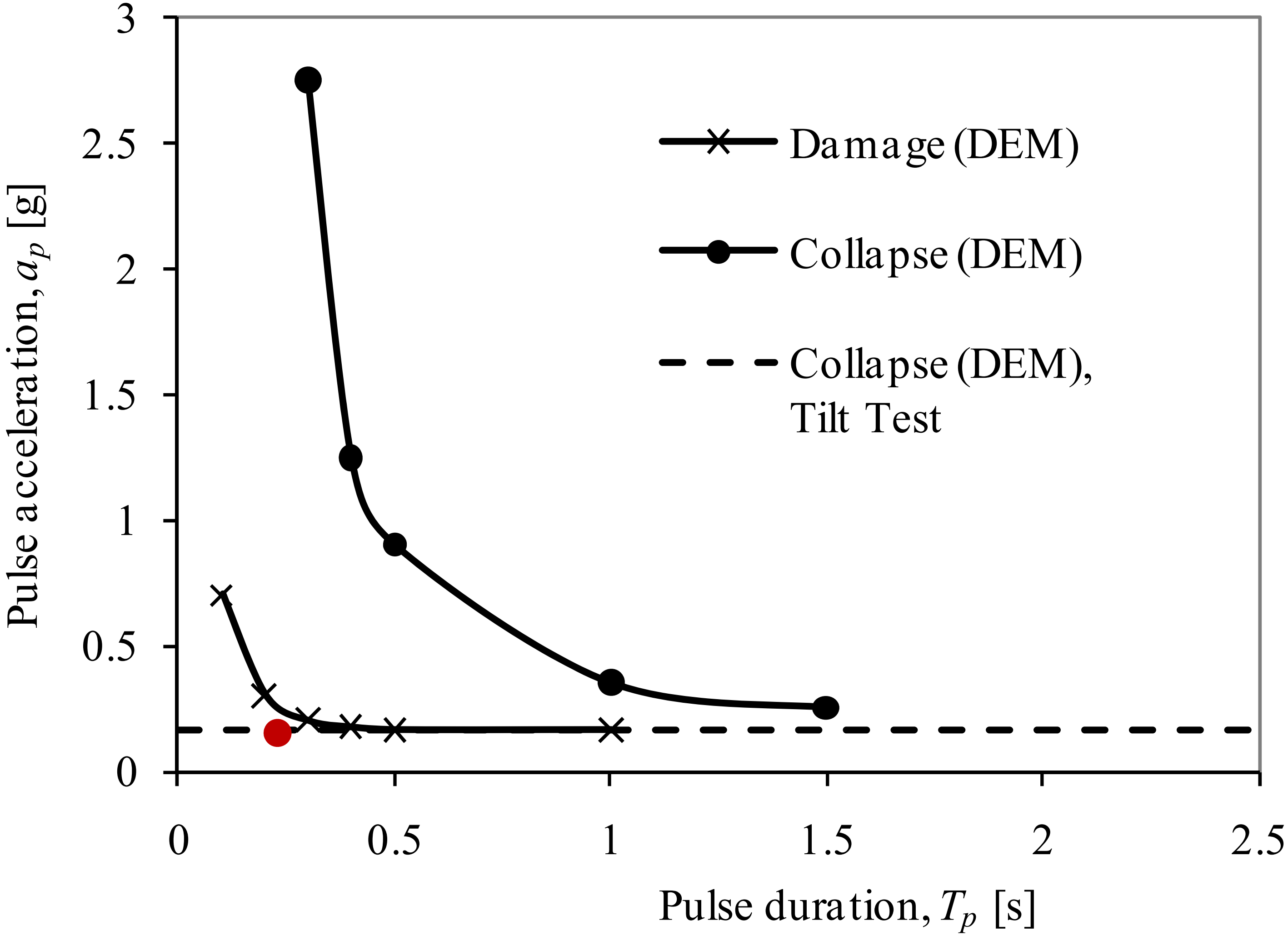
2. Direct overturning

3. Vibration / walk apart / dis-integration
   - Difficult to model
   - Practical solutions (connections)

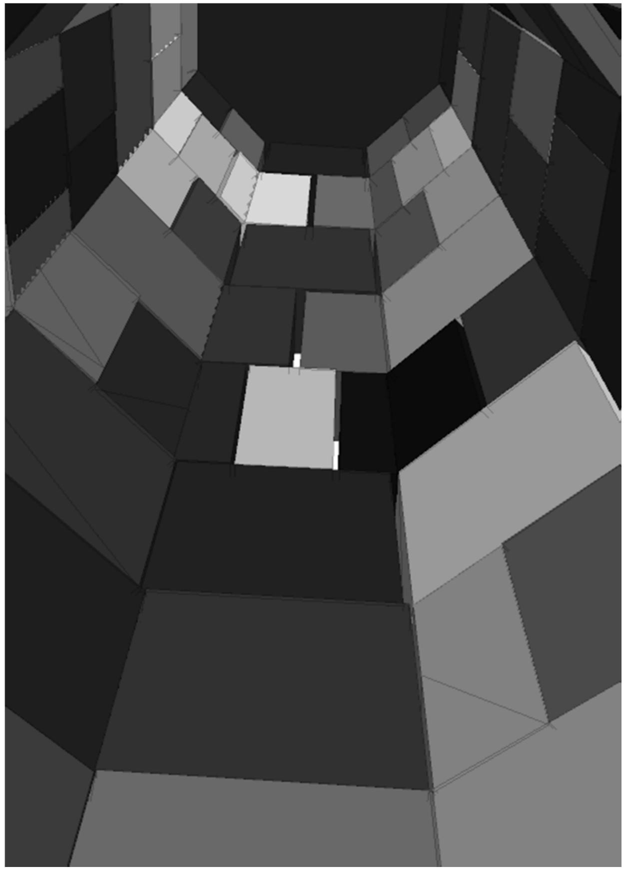
Seismic response

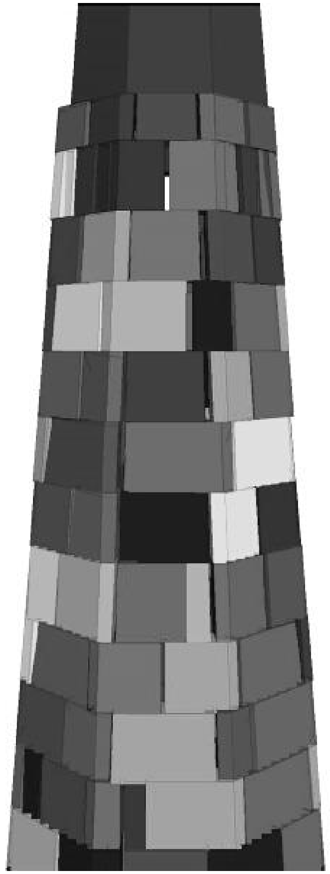


Seismic response



Seismic response





What drives collapse?

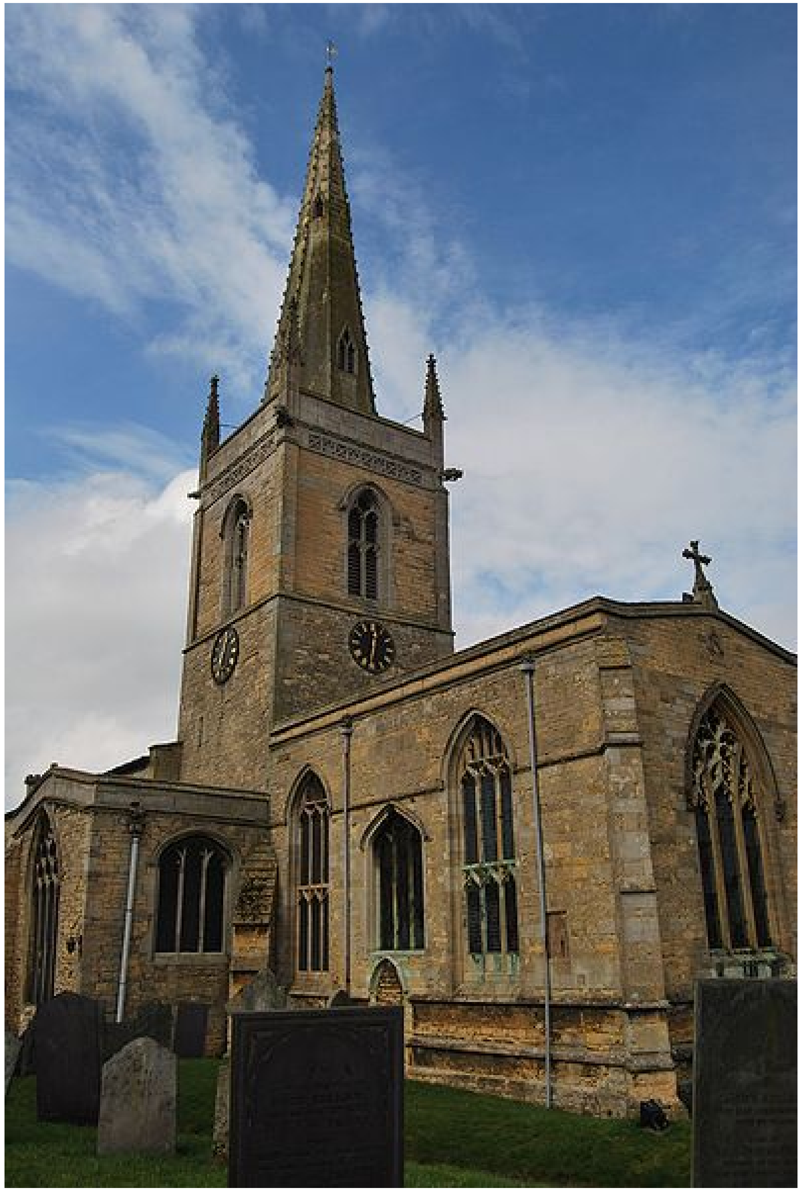
1. Elastic resonance?

2. Direct overturning

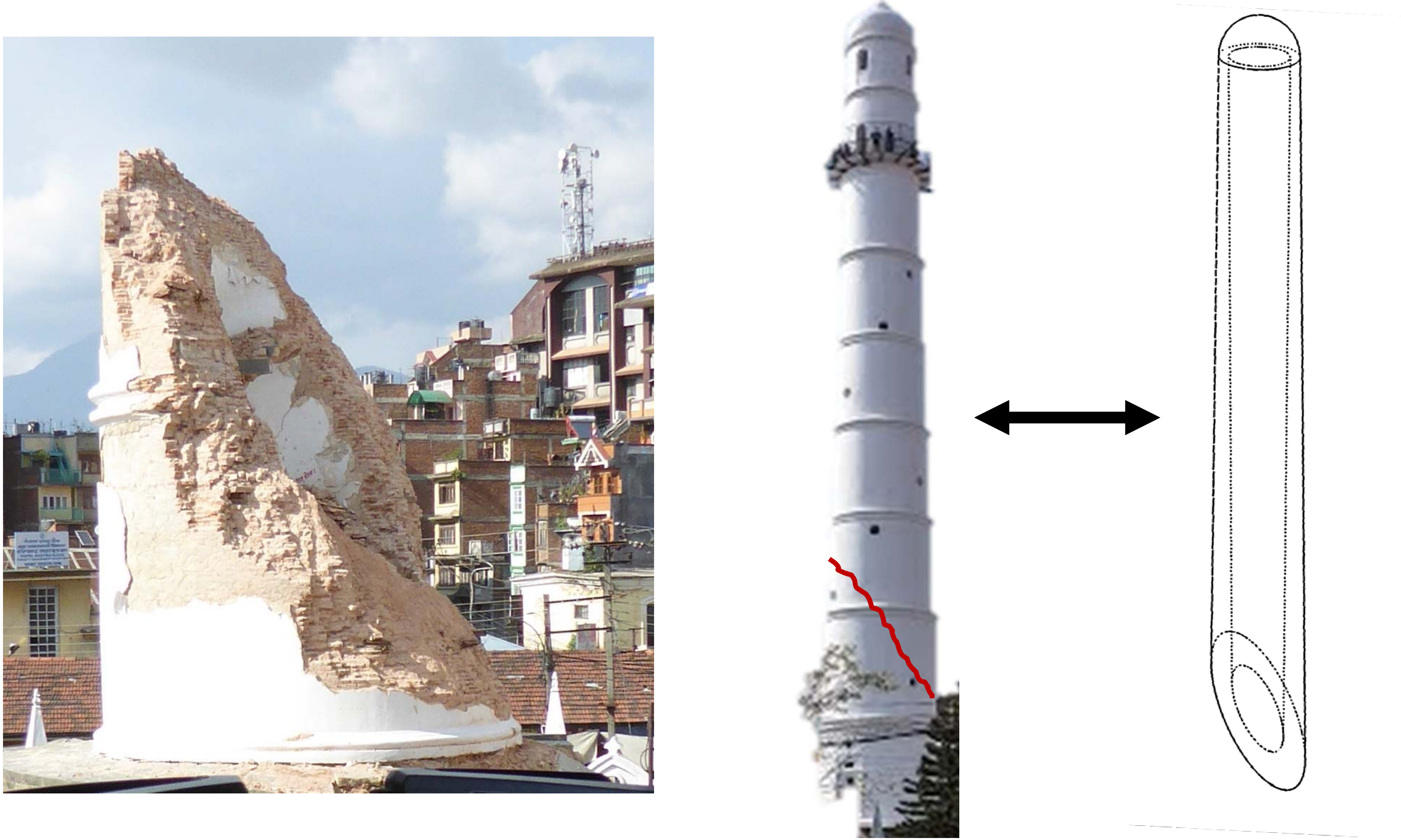
3. Vibration / walk apart / dis-integration
   – Interlock is important!

   – Local soil amplification important

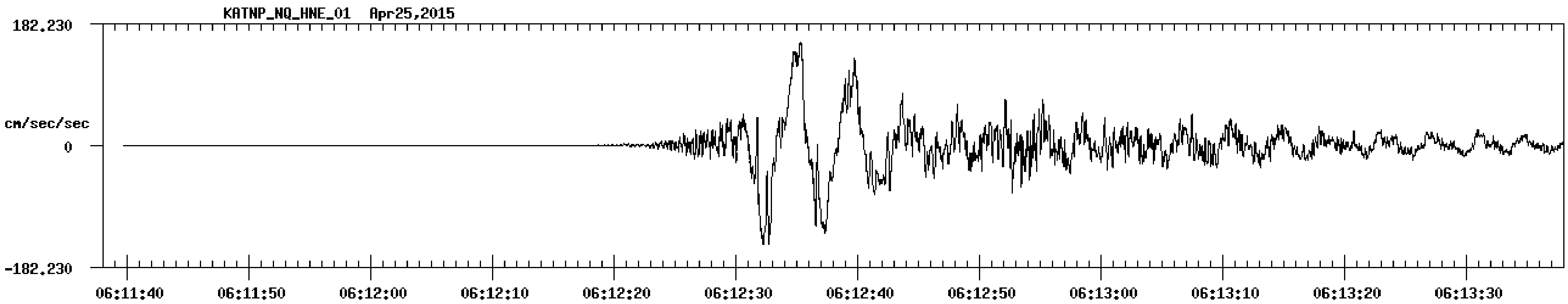
Solution

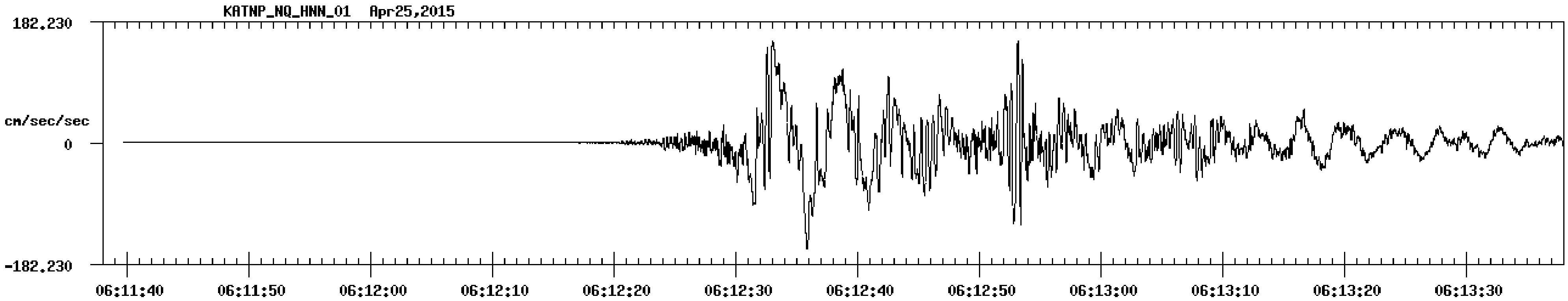


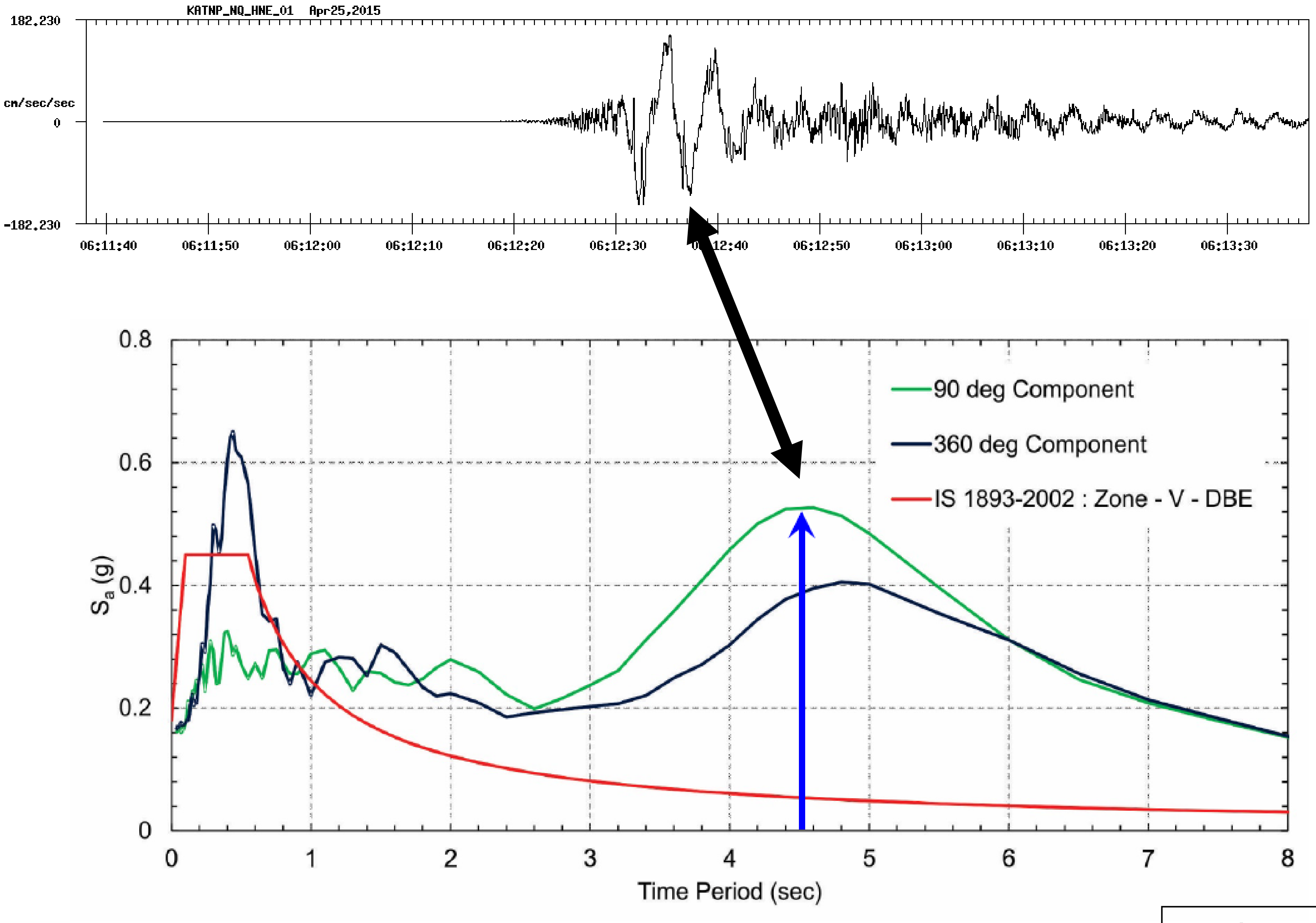
Case Study #3: Dharahara Tower, Nepal



Nepal Ground Motion







Rai et al. (2015)

Philippines: Brief Observations

Towers stocky, walls thick


Loay


Baclayan


Daius


Dimiao

Towers stocky, walls thick

Punta Cruz

Panglao

- Direct overturning less likely
- Elastic amplification smaller

Baclayon Bell Tower

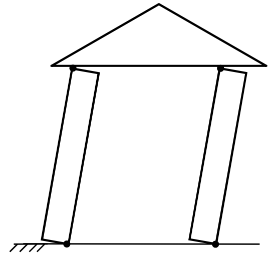
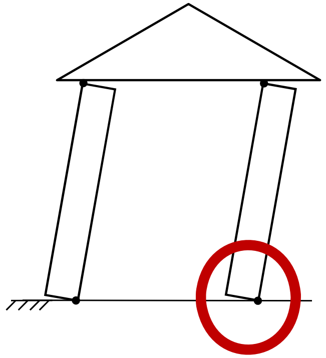


Photo by S. Kelley

Photo by A. Manding

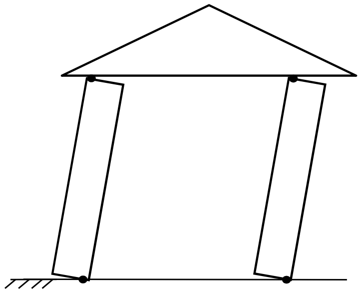
Dimiao



Bell Towers

- Tie top of walls

- Limit analysis:



- “Columns” of bell towers

Important considerations for towers

Global geometry:

- Slenderness
- Size/scale

Details:

- Openings (particularly bell towers)
- Quality of construction (masonry, roof ties)

Acknowledgments

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