Evidence of Seismic Resistance of Helical Foundations

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Outline

- IBC Seismic Loads
- Seismic Case Studies
- Seismic Damping of Helical Piles
- Example Seismic Design

Earthquake Loads (IBC 2006)

- Design to Resist Earthquake Loads
  - Exceptions:
    - One and Two-Family Dwellings in Seismic Design Categories A, B, or C where mapped short-period response < 0.4 g
    - Wood Frame Buildings in Accordance with Section 2308
    - Agricultural Storage Structures
  - Seismic Design Category
    - Based on Occupancy and Severity of Ground Motion
  - Site Class
    - Classification based on Soils Present

Seismic Design of Piers or Piles (IBC 2006)

- Seismic Design Category C
  - Interconnect Piles or Pile Caps with Ties
    - Capable of Tension or Compression Force, F_s

      $F_s = 0.1 \times P_c \times S_{DS}$

      P_c = Higher Column Load
  - Connection of Piles to Pile Cap
    - Provide Transverse Steel as Required for Column
    - Provide Tension Connection
  - Pile Splices
    - Develop Full Tensile Strength of Pile, or
    - Designed to Resist Seismic Load Combinations

Seismic Design of Piers or Piles (IBC 2006)

- Seismic Design Category D, E, or F
  - Meet Requirements of Seismic Design Category C
  - Design Details for Piles
    - Designed to Withstand Maximum Imposed Ground Motions
      - Lateral Resistance to Structure Seismic Forces
      - Liquefiable Strata
  - Connection of Piles to Pile Cap
    - Design Tension Connection for lesser of
      - 1.3 x Mechanical Tensile Capacity of Pile
      - 1.3 x Pullout Capacity of Pile
      - Seismic Load Combinations
    - Design Moment Connection for lesser of
      - Mechanical Axial, Shear, and Moment Capacity of Pile
      - Seismic Load Combinations

Earthquake Loads (IBC 2006)

- Vertical Component, E_V
  - $E_V = 0.25\ S_{DS}\ D$ where,
    - S_{DS} = Short Period Design Acceleration
    - D = Dead Load
- Horizontal Component, E_H
  - $E_H = \rho\ Q_E$ where,
    - ρ = Redundancy Factor (1 to 1.5)
    - Q_E = Horizontal Seismic Forces (C_S W “Base Shear”)
    - C_S = Seismic Response Coefficient (I S_{DS}/R “Simplified”
    - W = Weight of Structure (Dead + Select Live Loads
    - R = Response Modification Coefficient (1.5 to 8)

Seismic Design Category (2006 IBC)

TABLE 1613.5.6(1)
SEISMIC DESIGN CATEGORY BASED ON SHORT-PERIOD RESPONSE ACCELERATIONS

VALUE OF S_{DS}	OCCUPANCY CATEGORY		
	I or II	III	IV
$S_{DS} < 0.167g$	A	A	A
$0.167g \le S_{DS} < 0.33g$	B	B	C
$0.33g \le S_{DS} < 0.50g$	C	C	D
$0.50g \le S_{DS}$	D	D	D

<u>Seismic Design Category E:</u>
Occupancy I, II, or III
with $S_{D1} \geq 0.75$

<u>Seismic Design Category F:</u>
Occupancy IV
with $S_{D1} \geq 0.75$

Occupancy Category (IBC 2006)

- I : Agricultural and Storage Facilities
- II: Other Structures
- III: High Occupancy Structures
- IV: Essential Facilities

Earthquake Loads (IBC 2006)

- Adjusted Maximum Acceleration
  - $S_{MS} = F_a S_s$
- Design Acceleration
  - $S_{DS} = 2/3\ S_{MS}$

0.2 s Acceleration, S_s (2006 IBC)

Site Coefficients (2006 IBC)

TABLE 1613.5.3(1)
VALUES OF SITE COEFFICIENT F_a [a]

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIOD				
	$S_s \le 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	Note b	Note b	Note b	Note b	Note b

a. Use straight-line interpolation for intermediate values of mapped spectral response acceleration at short period, S_s.
b. Values shall be determined in accordance with Section 11.4.7 of ASCE 7.

Site Class Definitions (2006 IBC)

TABLE 1613.5.2
SITE CLASS DEFINITIONS

SITE CLASS	SOIL PROFILE NAME	AVERAGE PROPERTIES IN TOP 100 feet, SEE SECTION 1613.5.5		
		Soil shear wave velocity, $\bar{v}_s$, (ft/s)	Standard penetration resistance, $\bar{N}$	Soil undrained shear strength, $\bar{s}_u$, (psf)
A	Hard rock	$\bar{v}_s > 5,000$	N/A	N/A
B	Rock	$2,500 < \bar{v}_s \le 5,000$	N/A	N/A
C	Very dense soil and soft rock	$1,200 < \bar{v}_s \le 2,500$	$\bar{N} > 50$	$\bar{s}_u \ge 2,000$
D	Stiff soil profile	$600 \le \bar{v}_s \le 1,200$	$15 \le \bar{N} \le 50$	$1,000 \le \bar{s}_u \le 2,000$
E	Soft soil profile	$\bar{v}_s < 600$	$\bar{N} < 15$	$\bar{s}_u < 1,000$
E	—	Any profile with more than 10 feet of soil having the following characteristics: 1. Plasticity index $PI > 20$, 2. Moisture content $w \ge 40\%$, and 3. Undrained shear strength $\bar{s}_u < 500$ psf		
F	—	Any profile containing soils having one or more of the following characteristics: 1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays ($H > 10$ feet of peat and/or highly organic clay where H = thickness of soil) 3. Very high plasticity clays ($H > 25$ feet with plasticity index $PI > 75$) 4. Very thick soft/medium stiff clays ($H > 120$ feet)		

For SI: 1 foot = 304.8 mm, 1 square foot = 0.0929 m², 1 pound per square foot = 0.0479 kPa. N/A = Not applicable

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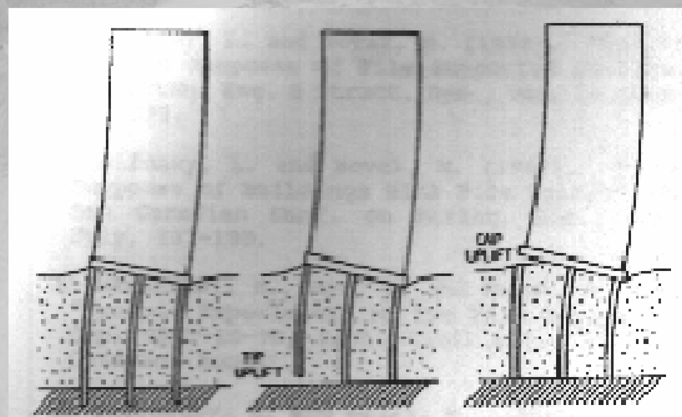
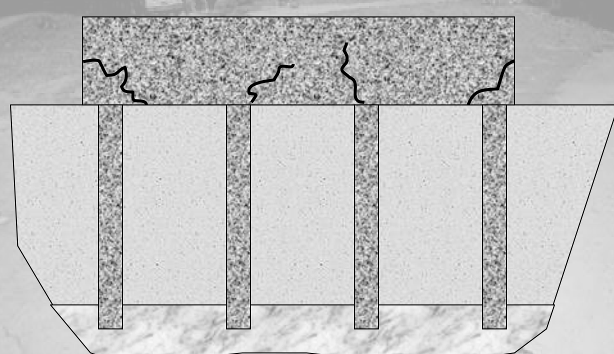
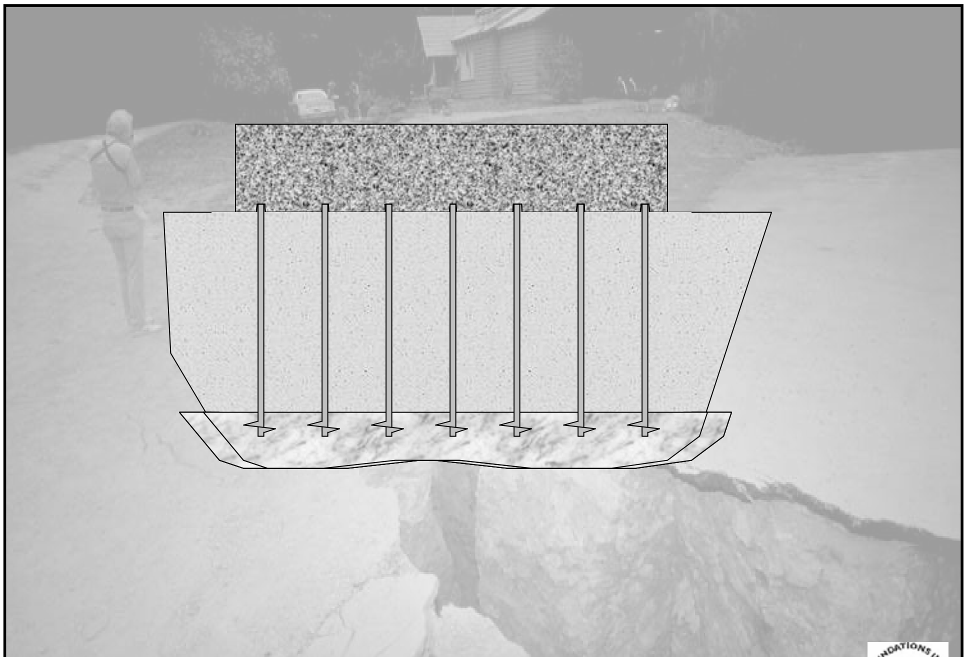
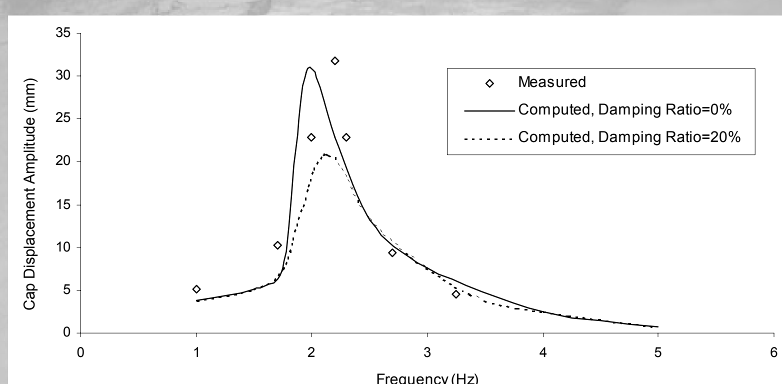
Common Pile Failures







Damping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Frequency (Hz)
Measured
Computed, Damping Ratio=0%
Computed, Damping Ratio=20%
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6

Damping

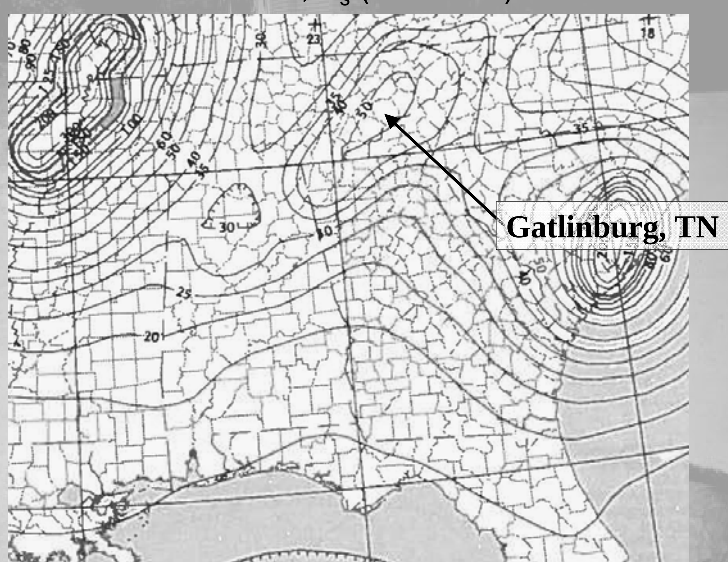
- Pile Head Accelerations can be Reduced by 60% due to Damping

(Tabesh and Poulos, 1999)

Seismic Parameters:

S_S = 0.50

0.2 s Acceleration, S_s (2006 IBC)



Seismic Parameters: Site Class Definitions (2006 IBC)

S_S = 0.50

Site Class = D

TABLE 1613.5.2
SITE CLASS DEFINITIONS

SITE CLASS	SOIL PROFILE NAME	AVERAGE PROPERTIES IN TOP 100 feet, SEE SECTION 1613.5.5		
		Soil shear wave velocity, $\bar{v}_s$, (ft/s)	Standard penetration resistance, $\bar{N}$	Soil undrained shear strength, $\bar{s}_u$, (psf)
A	Hard rock	$\bar{v}_s > 5{,}000$	N/A	N/A
B	Rock	$2{,}500 < \bar{v}_s \le 5{,}000$	N/A	N/A
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \le 2{,}500$	$\bar{N} > 50$	$\bar{s}_u \ge 2{,}000$
D	Stiff soil profile	$600 \le \bar{v}_s \le 1{,}200$	$15 \le \bar{N} \le 50$	$1{,}000 \le \bar{s}_u \le 2{,}000$
E	Soft soil profile	$\bar{v}_s < 600$	$\bar{N} < 15$	$\bar{s}_u < 1{,}000$

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Seismic Parameters: Site Coefficients (2006 IBC)

S_S = 0.50

Site Class = D

F_a = 1.4

TABLE 1613.5.3(1)
VALUES OF SITE COEFFICIENT F_a [a]

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIOD				
	$S_s \le 0.25$	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	Note b	Note b	Note b	Note b	Note b

a. Use straight-line interpolation for intermediate values of mapped spectral response acceleration at short period, S_s.
b. Values shall be determined in accordance with Section 11.4.7 of ASCE 7.

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Earthquake Loads (IBC 2006)

Seismic Parameters:

$S_S = 0.50$

Site Class = D

$F_a = 1.4$

$S_{DS} = 0.47$

- Adjusted Maximum Acceleration
  - $S_{MS} = F_a S_s$ – $S_{MS} = 1.4\ (0.5) = 0.7$
- Design Acceleration
  - $S_{DS} = 2/3\ S_{MS}$ – $S_{DS} = 2/3\ (0.7) = 0.47$

Occupancy Category (IBC 2006)

Seismic Parameters:

$S_S = 0.50$

Site Class = D

$F_a = 1.4$

$S_{DS} = 0.47$

Occup. = III

- I : Agricultural and Storage Facilities
- II: Other Structures
- III: High Occupancy Structures
- IV: Essential Facilities

Seismic Parameters:

Seismic Design Category (2006 IBC)

S_S = 0.50

Site Class = D

F_a = 1.4

S_{DS} = 0.47

Occup. = III

S.D.C. = C

TABLE 1613.5.6(1)
SEISMIC DESIGN CATEGORY BASED ON SHORT-PERIOD RESPONSE ACCELERATIONS

VALUE OF S_{DS}	OCCUPANCY CATEGORY		
	I or II	III	IV
$S_{DS} < 0.167g$	A	A	A
$0.167g \le S_{DS} < 0.33g$	B	B	C
$0.33g \le S_{DS} < 0.50g$	C	C	D
$0.50g \le S_{DS}$	D	D	D

Seismic Parameters:

Seismic Design of Piers or Piles (IBC 2006)

S_S = 0.50

Site Class = D

F_a = 1.4

S_{DS} = 0.47

Occup. = III

S.D.C. = C

F_S = 2.4 kips

- Seismic Design Category C
  - Interconnect Piles or Pile Caps with Ties
    - Capable of Tension or Compression Force, F_s
      - $F_s = 0.1 \times P_c \times S_{DS}$ = 0.1(50)(0.47) = 2.4 kips
      - P_c = Higher Column Load = 50 kips
  - Connection of Piles to Pile Cap
    - Provide Transverse Steel as Required for Column
    - Provide Tension Connection
  - Pile Splices
    - Develop Full Tensile Strength of Pile, or
    - Designed to Resist Seismic Load Combinations

Seismic Parameters:

S_S = 0.50

Site Class = D

F_a = 1.4

S_{DS} = 0.47

Occup. = III

S.D.C. = C

F_S = 2.4 kips

E_V = 5.9 kips

Earthquake Loads (IBC 2006)

- Vertical Component, E_V
  - $E_V = 0.25\ S_{DS}\ D$ where,
    - S_{DS} = Short Period Design Acceleration
    - D = Dead Load
  - E_V = 0.25 (0.47) (50 kips)
  - E_V = 5.9 kips

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What About Damping?

- Re-do Example with 60% Damping

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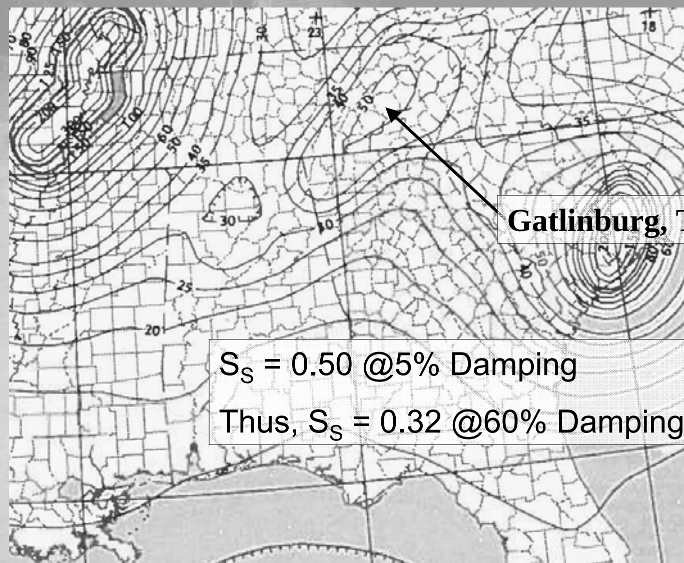
Seismic Parameters:

0.2 s Acceleration, S_s (2006 IBC)

$S_S = 0.32$



$S_S = 0.50$ @5% Damping

Thus, $S_S = 0.32$ @60% Damping

Seismic Parameters:

Site Class Definitions (2006 IBC)

$S_S = 0.32$

Site Class = D

TABLE 1613.5.2
SITE CLASS DEFINITIONS

SITE CLASS	SOIL PROFILE NAME	AVERAGE PROPERTIES IN TOP 100 feet, SEE SECTION 1613.5.5		
		Soil shear wave velocity, $\bar{v}_s$, (ft/s)	Standard penetration resistance, $\bar{N}$	Soil undrained shear strength, $\bar{s}_u$, (psf)
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C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \le 2{,}500$	$\bar{N} > 50$	$\bar{s}_u \ge 2{,}000$
D	Stiff soil profile	$600 \le \bar{v}_s \le 1{,}200$	$15 \le \bar{N} \le 50$	$1{,}000 \le \bar{s}_u \le 2{,}000$
E	Soft soil profile	$\bar{v}_s < 600$	$\bar{N} < 15$	$\bar{s}_u < 1{,}000$

Seismic Parameters:

Site Coefficients (2006 IBC)

S_S = 0.32

Site Class = D

F_a = 1.5

TABLE 1613.5.3(1)
VALUES OF SITE COEFFICIENT F_a [a]

SITE CLASS	MAPPED SPECTRAL RESPONSE ACCELERATION AT SHORT PERIOD					
	$S_s \le 0.25$	S_S=0.32	$S_s = 0.50$	$S_s = 0.75$	$S_s = 1.00$	$S_s \ge 1.25$
A	0.8		0.8	0.8	0.8	0.8
B	1.0		1.0	1.0	1.0	1.0
C	1.2		1.2	1.1	1.0	1.0
D	1.6	1.5	1.4	1.2	1.1	1.0
E	2.5		1.7	1.2	0.9	0.9
F	Note b		Note b	Note b	Note b	Note b

a. Use straight-line interpolation for intermediate values of mapped spectral response acceleration at short period, S_s.

b. Values shall be determined in accordance with Section 11.4.7 of ASCE 7.

Seismic Parameters:

Earthquake Loads (IBC 2006)

S_S = 0.32

Site Class = D

F_a = 1.5

S_{DS} = 0.32

- Adjusted Maximum Acceleration
  - $S_{MS} = F_a S_s$
  - S_{MS} = 1.5 (0.32) = 0.48
- Design Acceleration
  - S_{DS} = 2/3 S_{MS}
  - S_{DS} = 2/3 (0.48) = 0.32

Seismic Parameters:

Occupancy Category (IBC 2006)

S_S = 0.32

Site Class = D

F_a = 1.5

S_{DS} = 0.32

Occup. = III

- I : Agricultural and Storage Facilities
- II: Other Structures
- III: High Occupancy Structures
- IV: Essential Facilities

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Seismic Parameters:

Seismic Design Category (2006 IBC)

S_S = 0.32

Site Class = D

F_a = 1.5

S_{DS} = 0.32

Occup. = III

S.D.C. = B

TABLE 1613.5.6(1)
SEISMIC DESIGN CATEGORY BASED ON SHORT-PERIOD RESPONSE ACCELERATIONS

VALUE OF S_{DS}	OCCUPANCY CATEGORY		
	I or II	III	IV
$S_{DS} < 0.167g$	A	A	A
$0.167g \le S_{DS} < 0.33g$	B	B	C
$0.33g \le S_{DS} < 0.50g$	C	C	D
$0.50g \le S_{DS}$	D	D	D

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Seismic Parameters:

Seismic Design of Piers or Piles (IBC 2006)

S_S = 0.32
Site Class = D
F_a = 1.5
S_{DS} = 0.32
Occup. = III
S.D.C. = B
F_S = na

- Seismic Design Category A&B
  - No Special Seismic Requirements

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Seismic Parameters:

Earthquake Loads (IBC 2006)

S_S = 0.32
Site Class = D
F_a = 1.5
S_{DS} = 0.32
Occup. = III
S.D.C. = B
F_S = na
E_V = 4.0 kips

- Vertical Component, E_V
  - $E_V = 0.25\ S_{DS}\ D$ where,
    - S_{DS} = Short Period Design Acceleration
    - D = Dead Load
  - E_V = 0.25 (0.32) (50 kips)
  - Ev = 4.0 kips

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Comparison

With 5% Damping:	With 60% Damping:
S_S = 0.50	S_S = 0.32
Site Class = D	Site Class = D
F_a = 1.4	F_a = 1.5
S_{DS} = 0.47	S_{DS} = 0.32
Occup. = III	Occup. = III
S.D.C. = C	S.D.C. = B
F_S = 2.4 kips	F_S = na
E_V = 5.9 kips	E_V = 4.0 kips

Conclusions

- Historical Use of Helical Piles Suggests Excellent Earthquake Resistance
- More Research is Needed into Helical Pile Seismic Damping
- The Future of Helical Piles may be for Seismic Retrofit or New Foundations in Earthquake Prone Areas

Conclusions

…. hurry, before our Gatlinburg house looks like this…..

…. or this!