BEHAVIOR OF TWO LARGE MATS UNDER HIGH LOADS

Professor Jean-Louis BRIAUD

Distinguished Professor
Texas A&M University
and President of FedIGS

WASHINGTON MONUMENT
WASHINGTON DC (1887)

SAN JACINTO MONUMENT
HOUSTON (1936)

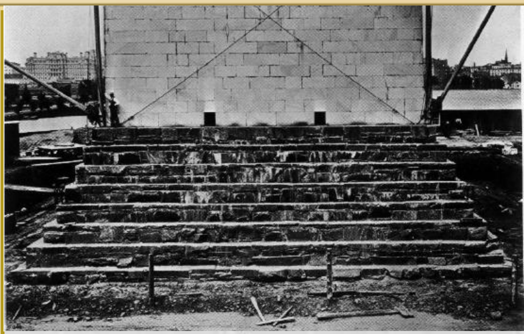
Washington Monument Case History

HISTORY

- George Washington, 1st President of USA
- Constructed in three phases:
  - 1848: 1st phase = construction begins
  - 1858: construction stops = no more money
  - 1879: 2nd phase = underpinning
  - 1880: 3rd phase = completion of the shaft
  - 1884: construction completed
- Settlement measured since 2nd phase in 1879

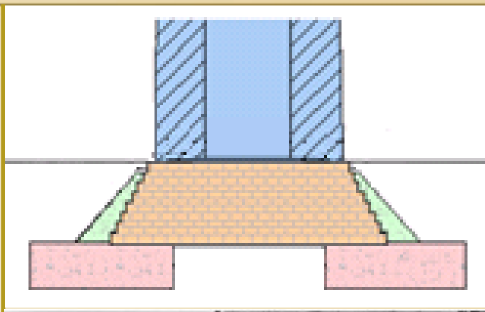
CONSTRUCTION

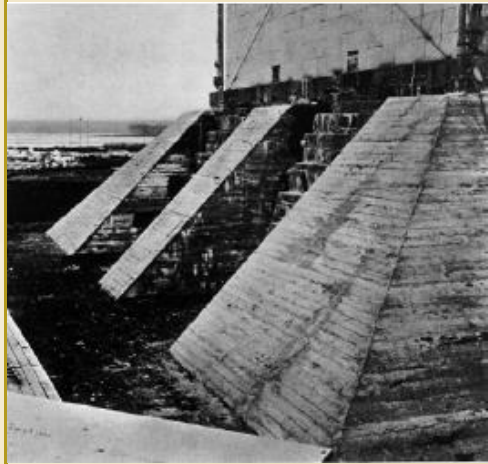
- Began in 1848 with architect Robert Mills
- Original foundation consisted of a stair stepped pyramid made of blue gneiss blocks
- Shaft made of marble blocks
- Construction was halted in 1858 with the shaft at a height of 55.5 m due to lack of funds

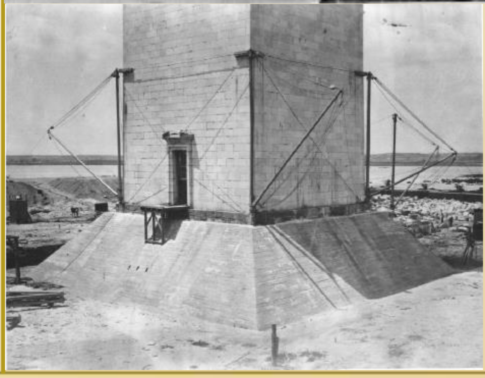


CONSTRUCTION

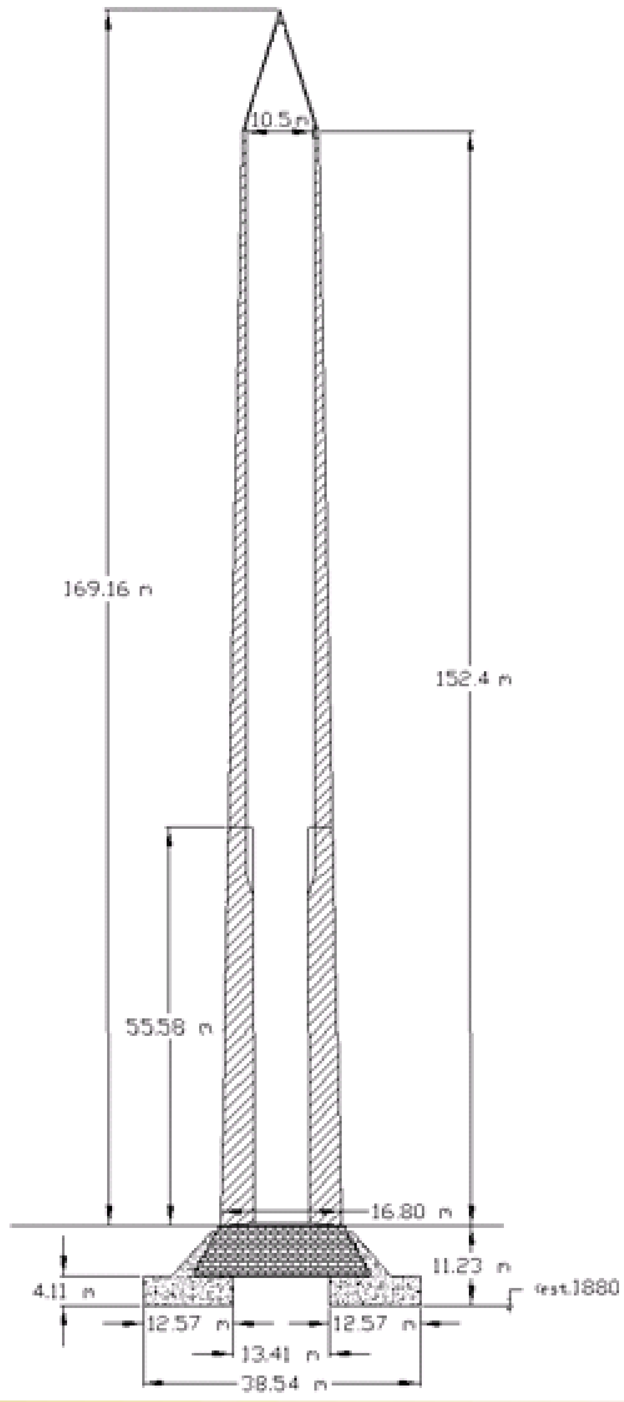
- Construction resumed in 1879, after the Civil War with Lt. Col. Casey of the US Army Corps of Engineers
- Casey considered the original foundation inadequate and decided to underpin it.
  - Increased foundation area
  - Founded on stiffer soil
- The Monument was completed in 1884

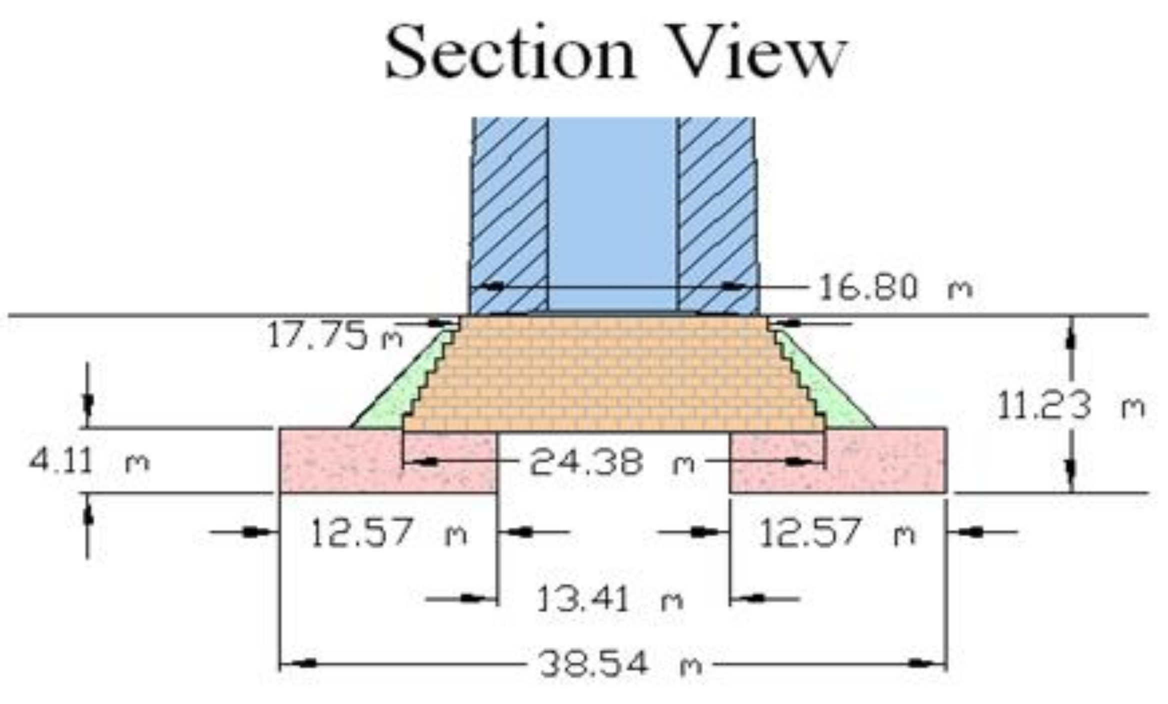




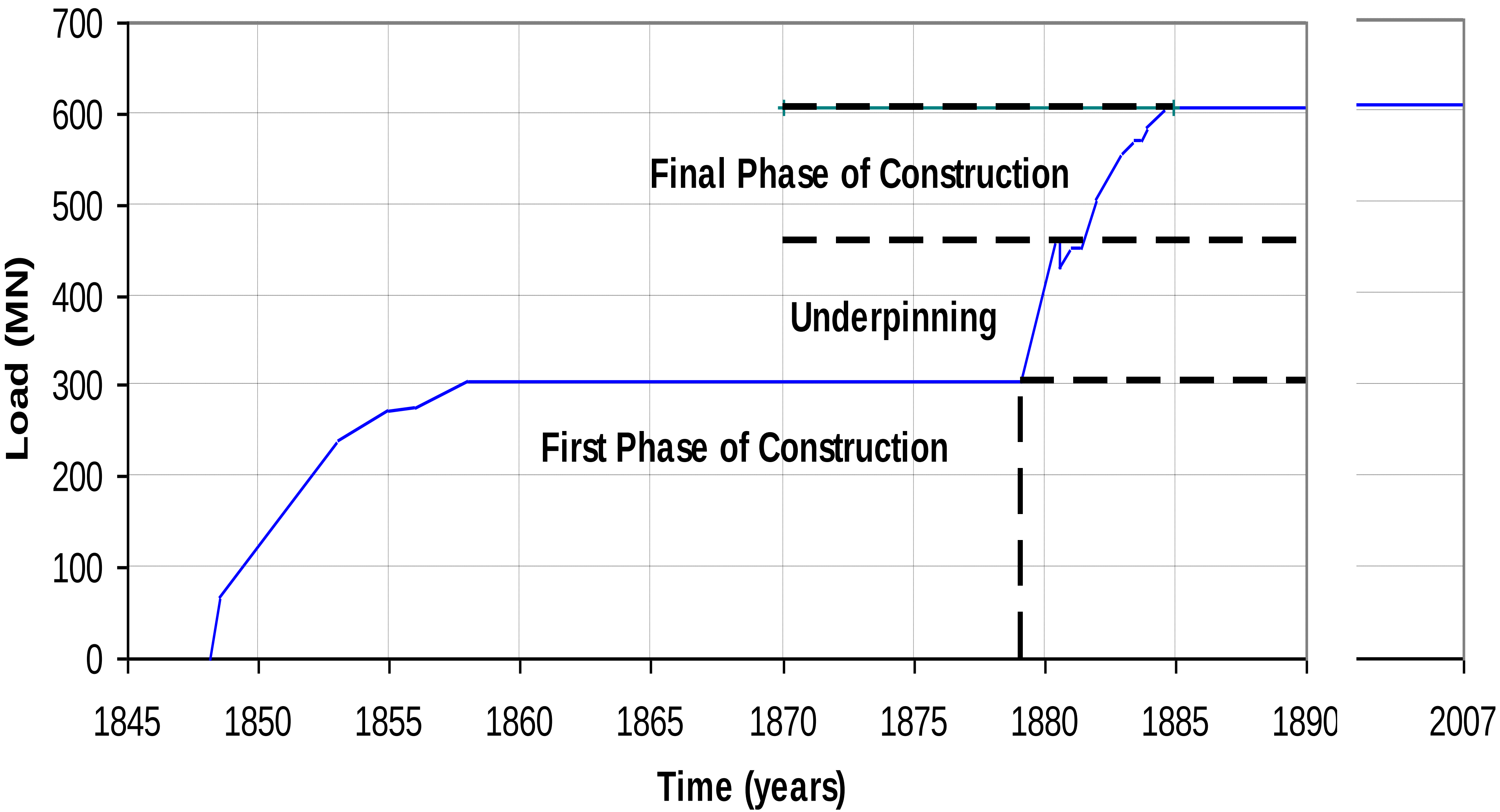


DIMENSIONS


10.5 m
169.16 m
152.4 m
55.58 m
16.80 m
11.23 m
4.11 m
(est.1880
12.57 m
12.57 m
13.41 m
38.54 m

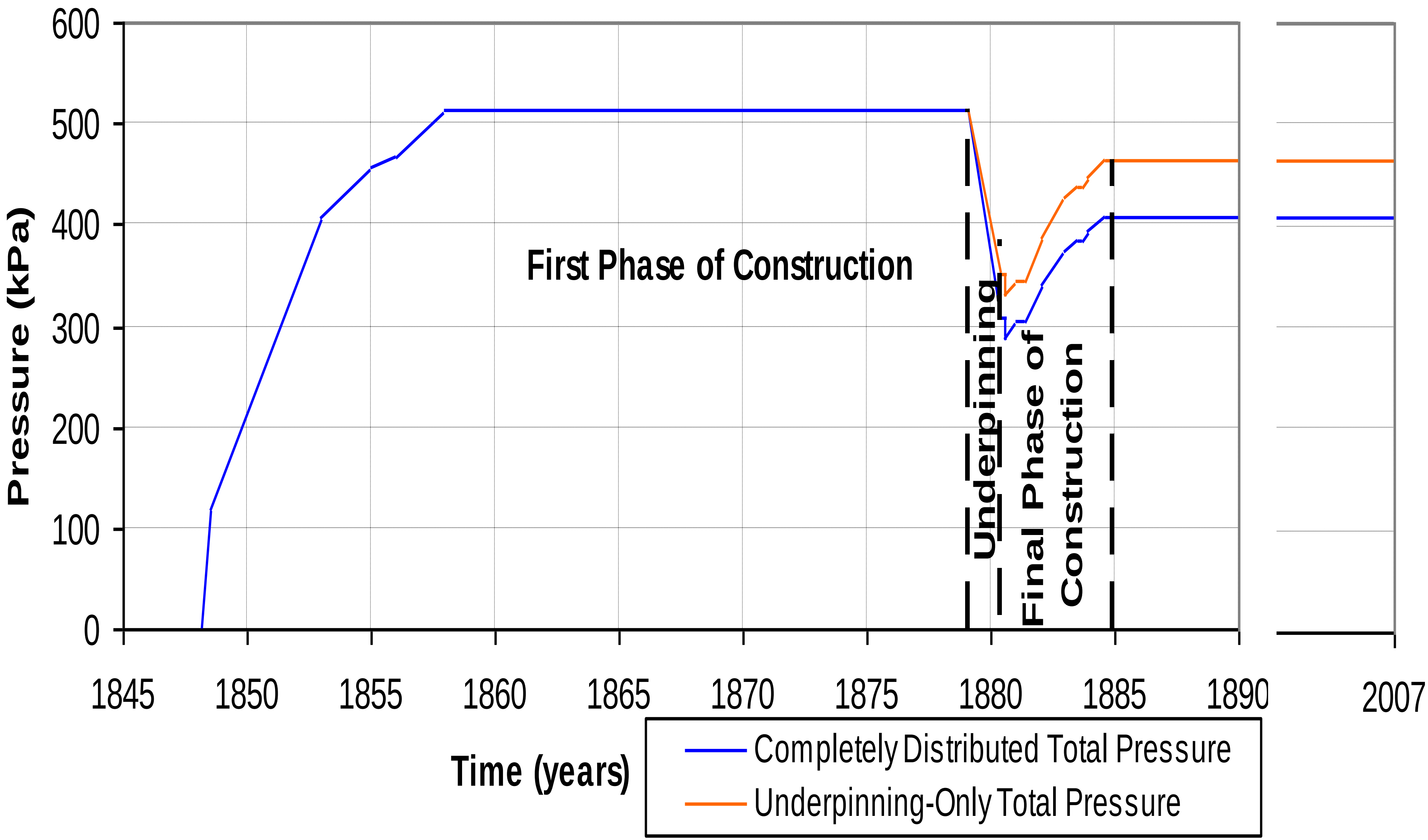

Section View
16.80 m
17.75 m
11.23 m
4.11 m
24.38 m
12.57 m
12.57 m
13.41 m
38.54 m

LOAD vs TIME


Load (MN)
700
600
500
400
300
200
100
0
Final Phase of Construction
Underpinning
First Phase of Construction
1845
1850
1855
1860
1865
1870
1875
1880
1885
1890
2007
Time (years)

PRESSURE vs TIME

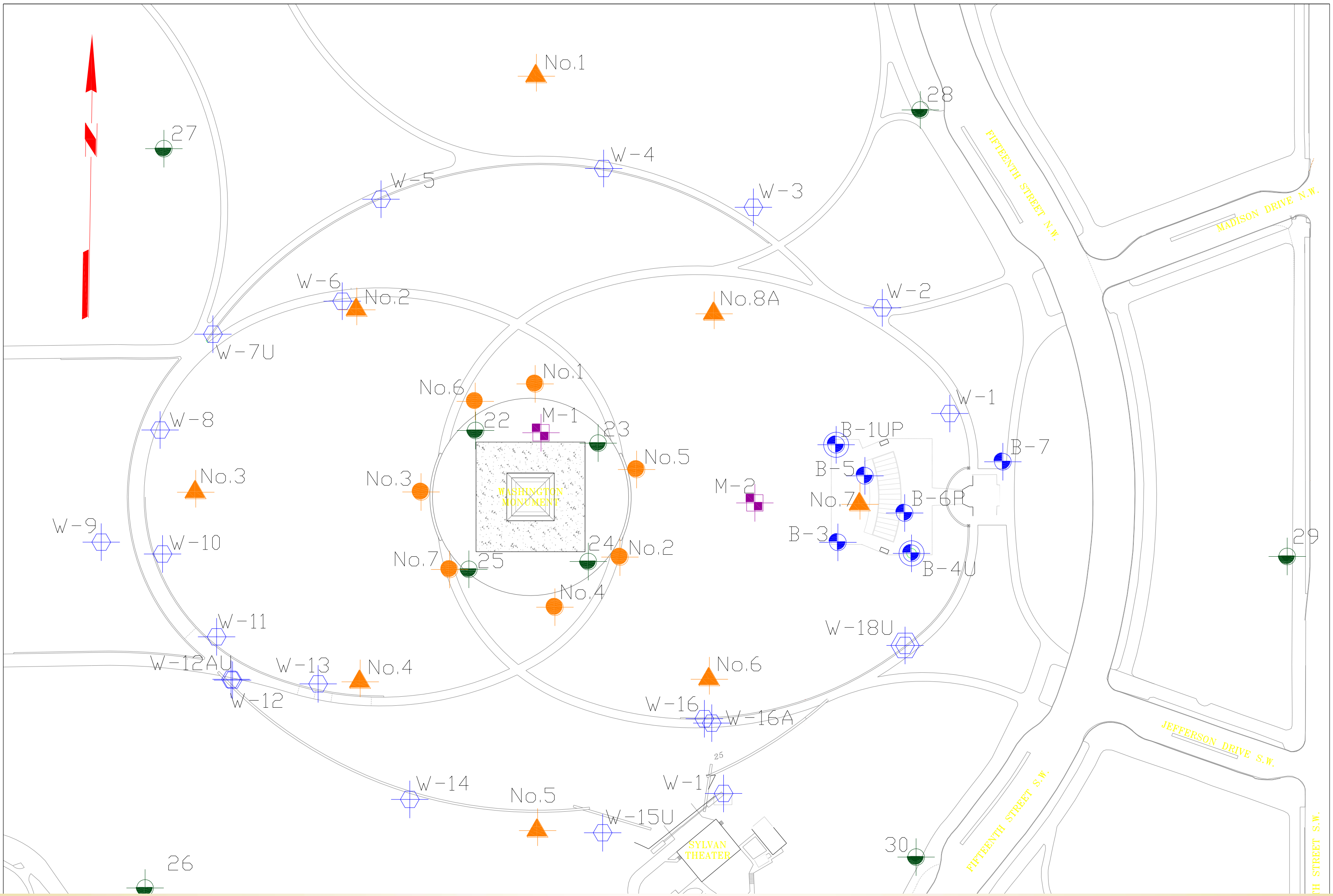
TEXAS A&M UNIVERSITY



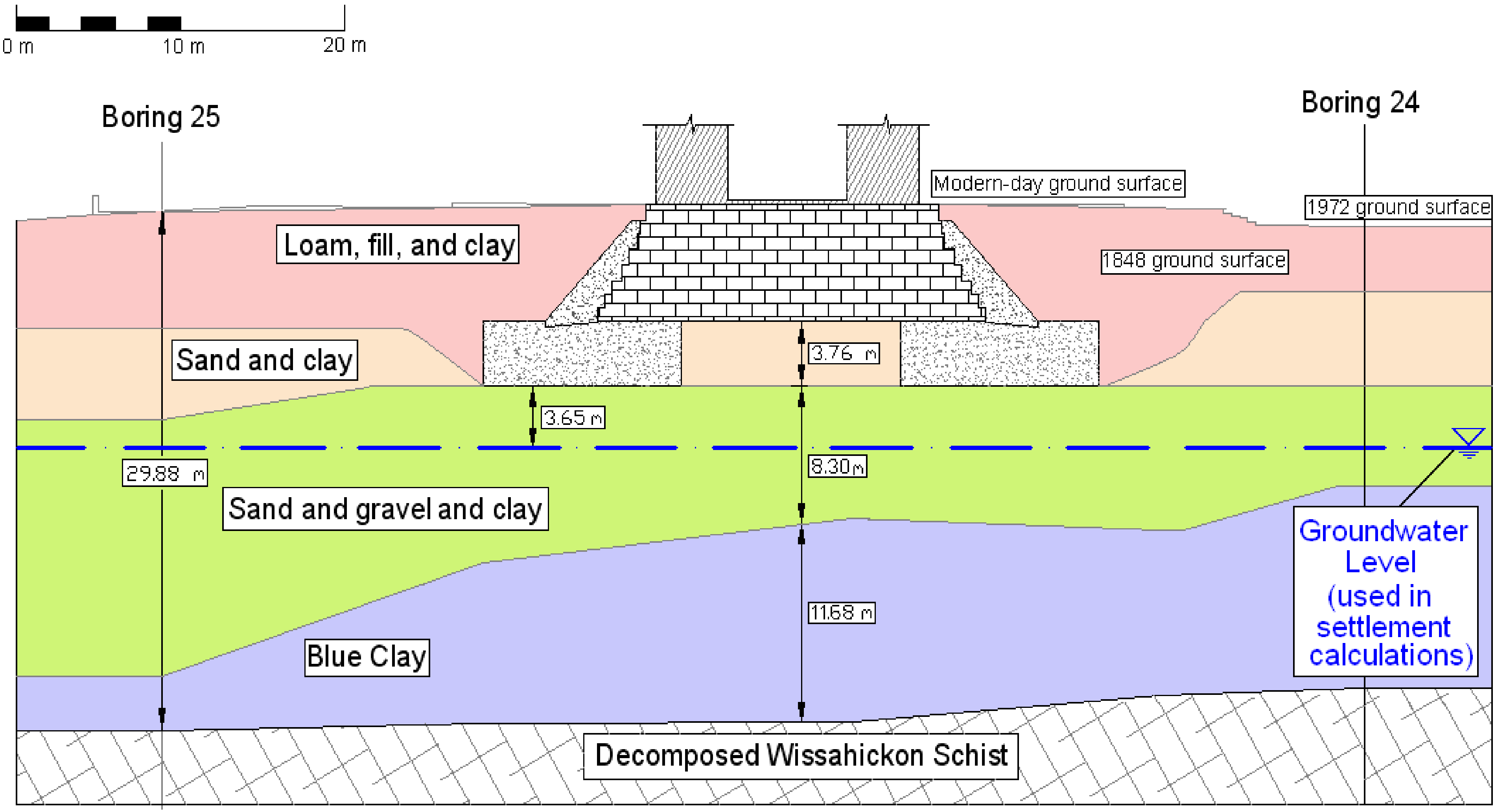
WEIGHT

- Weight of original foundation: 70 MN (Pressure = 118 kPa)
- Weight at end of Phase 1: 305 MN (Pressure = 513 kPa)
- Weight of new foundation: 153.8 MN
- Final weight of Washington Monument: 607.7 MN (Pressure = 465 kPa)
  - San Jacinto Monument: 313 MN
  - Tower of Pisa: 142 MN
  - Eiffel Tower: 94 MN
- Earth terrace: 86.4 kPa

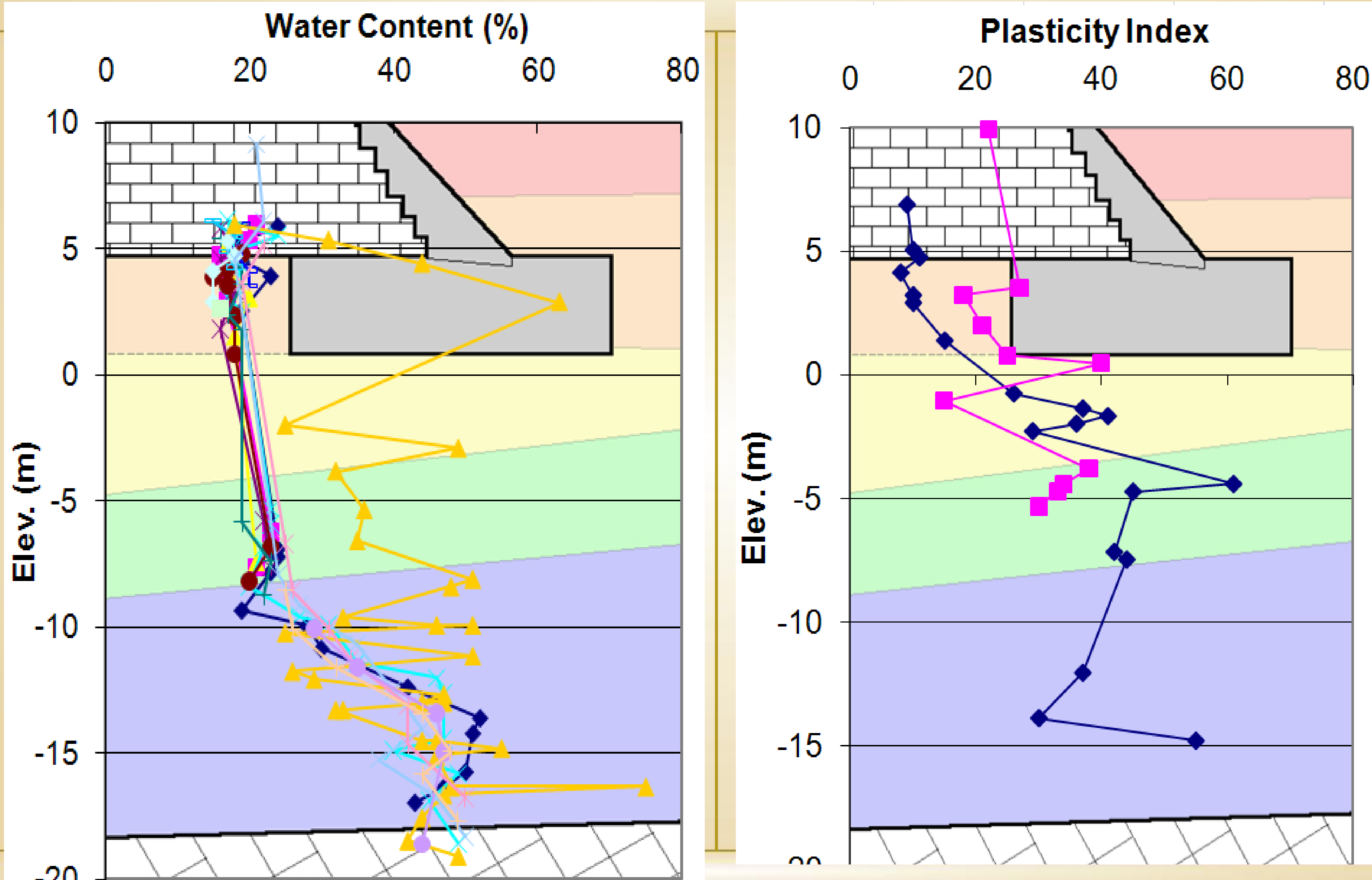
51 SOIL BORINGS DEEPEST 38 m



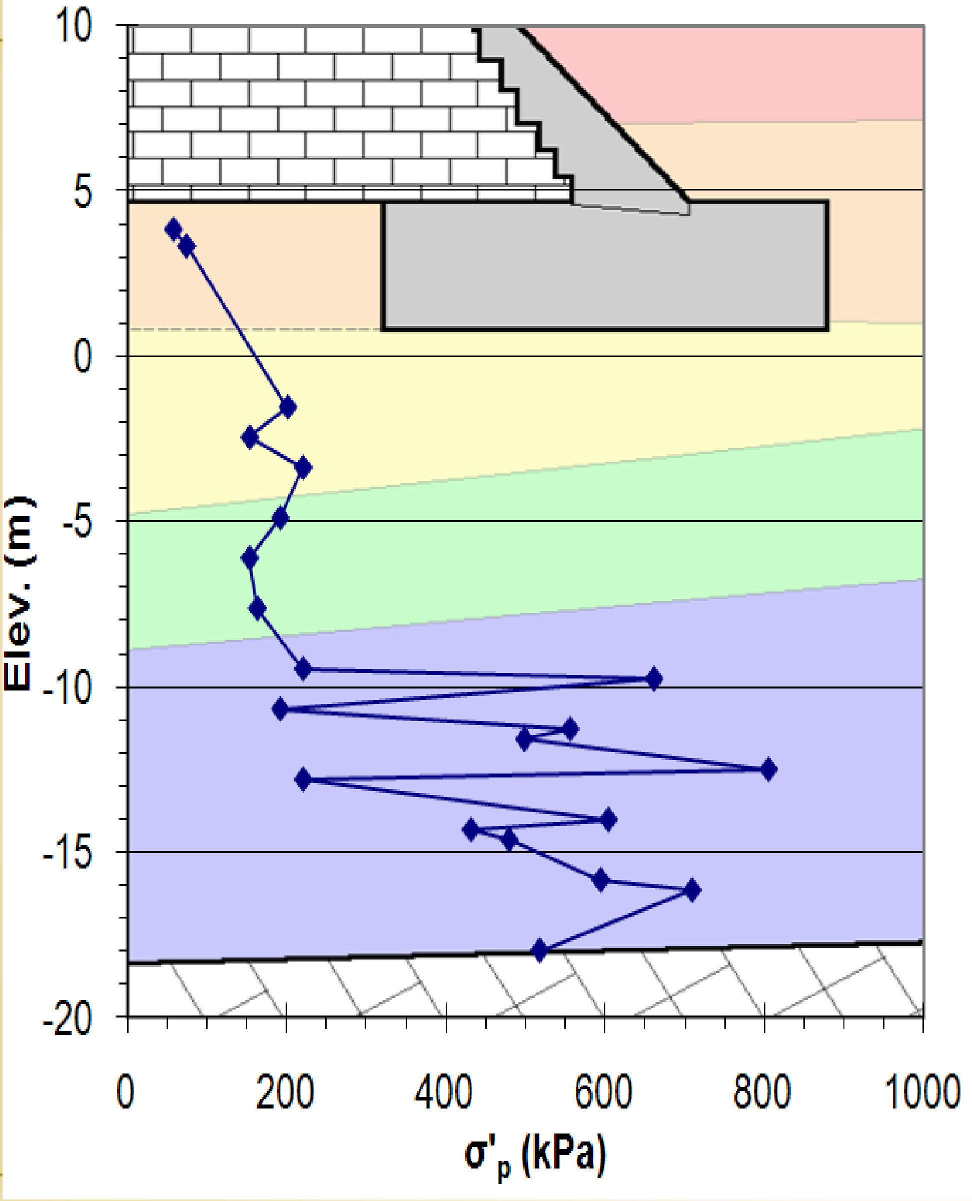
SOIL STRATIGRAPHY

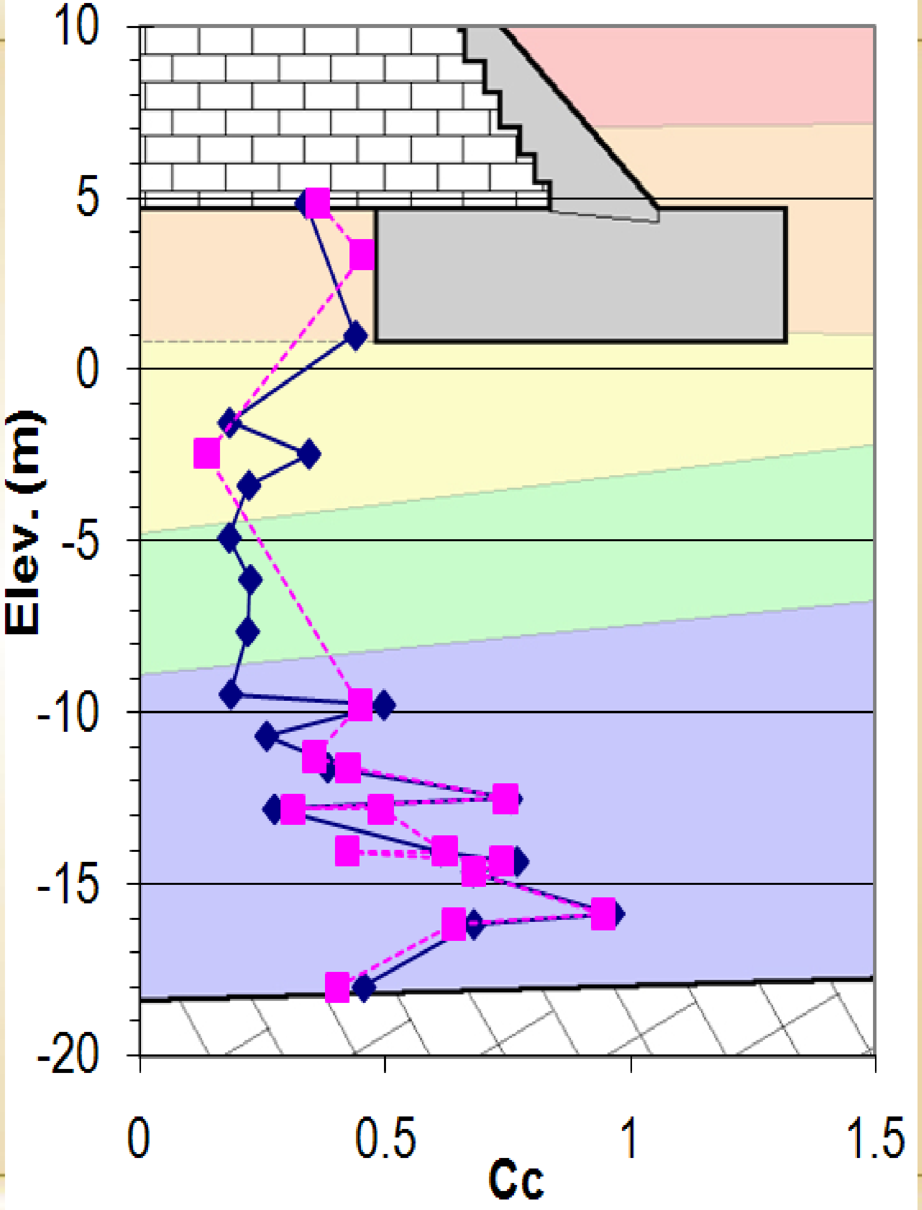


SOIL PROPERTIES

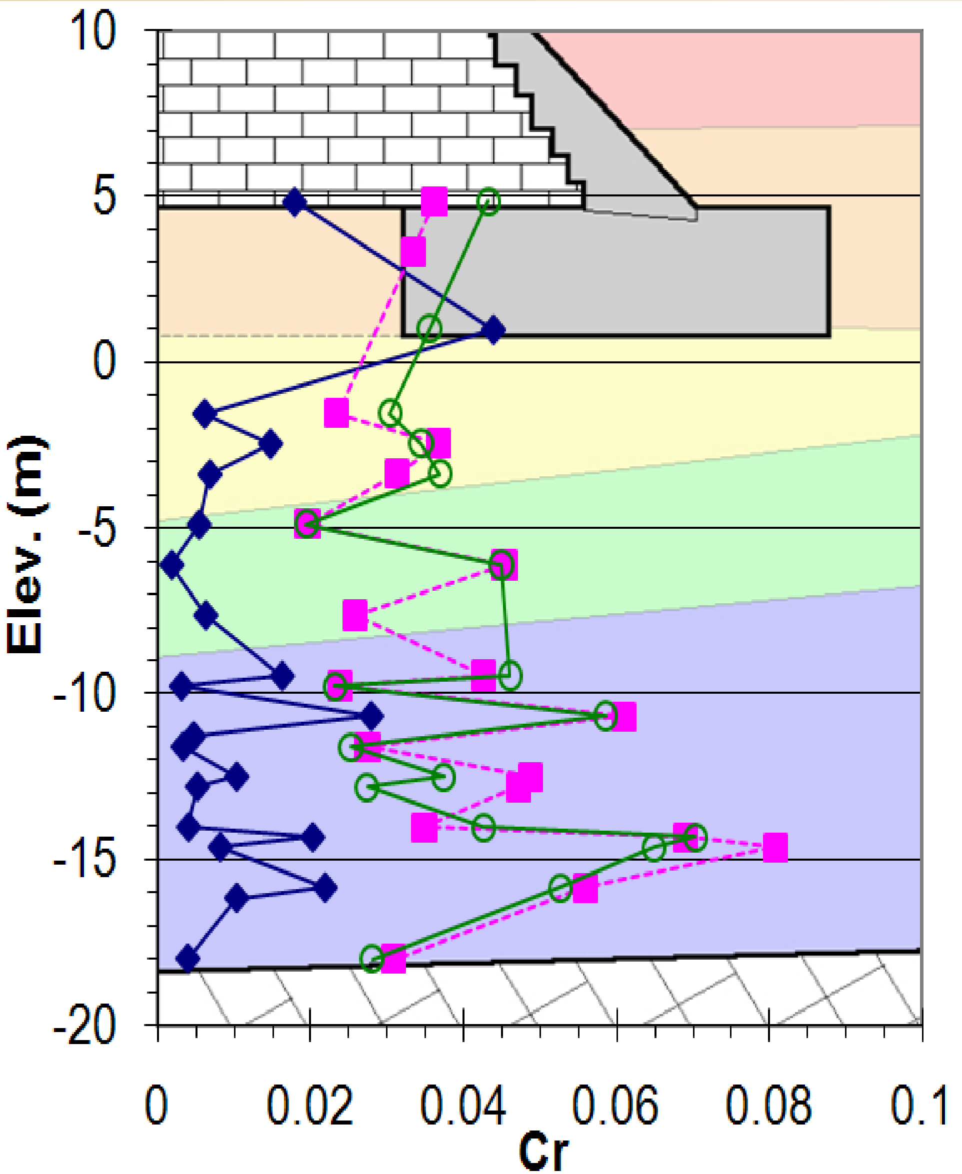


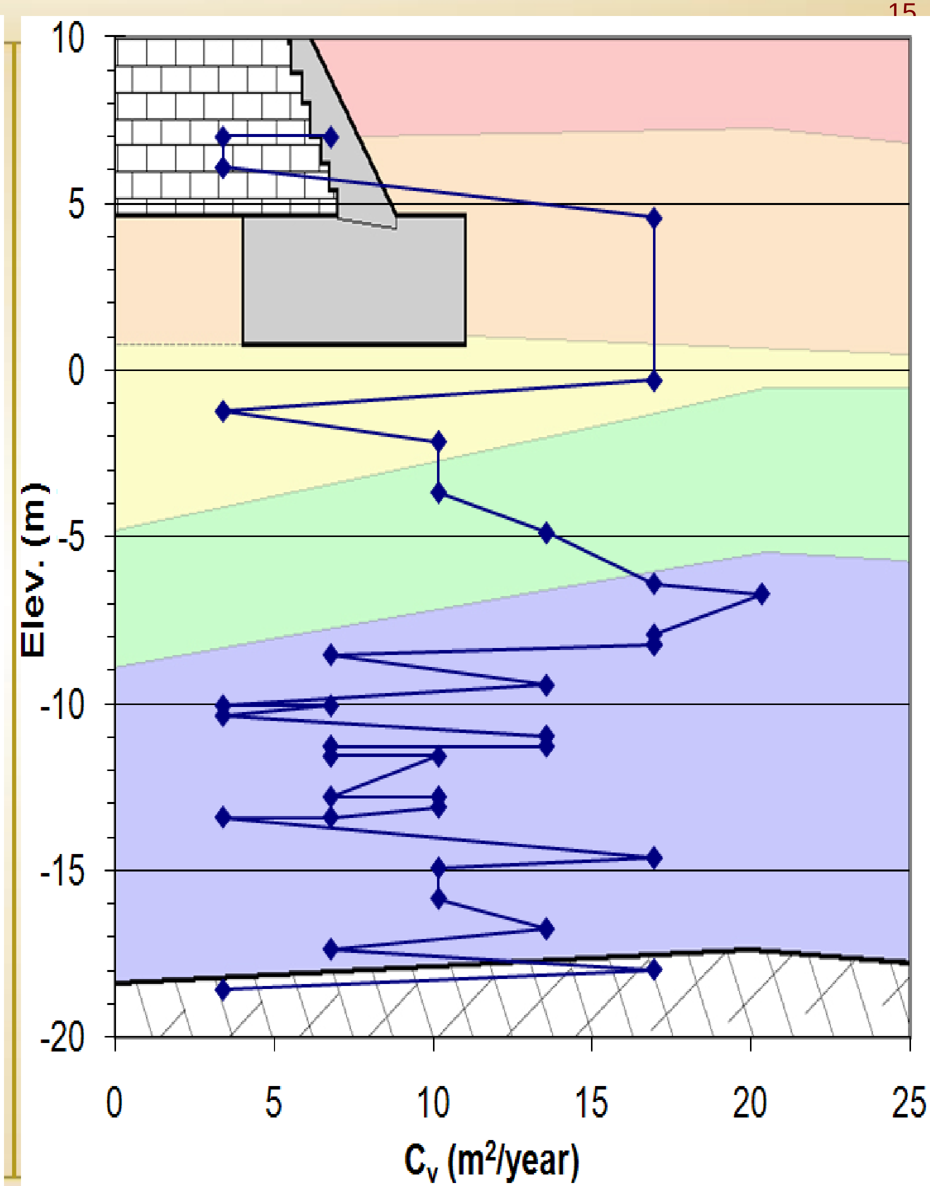
SOIL PROPERTIES





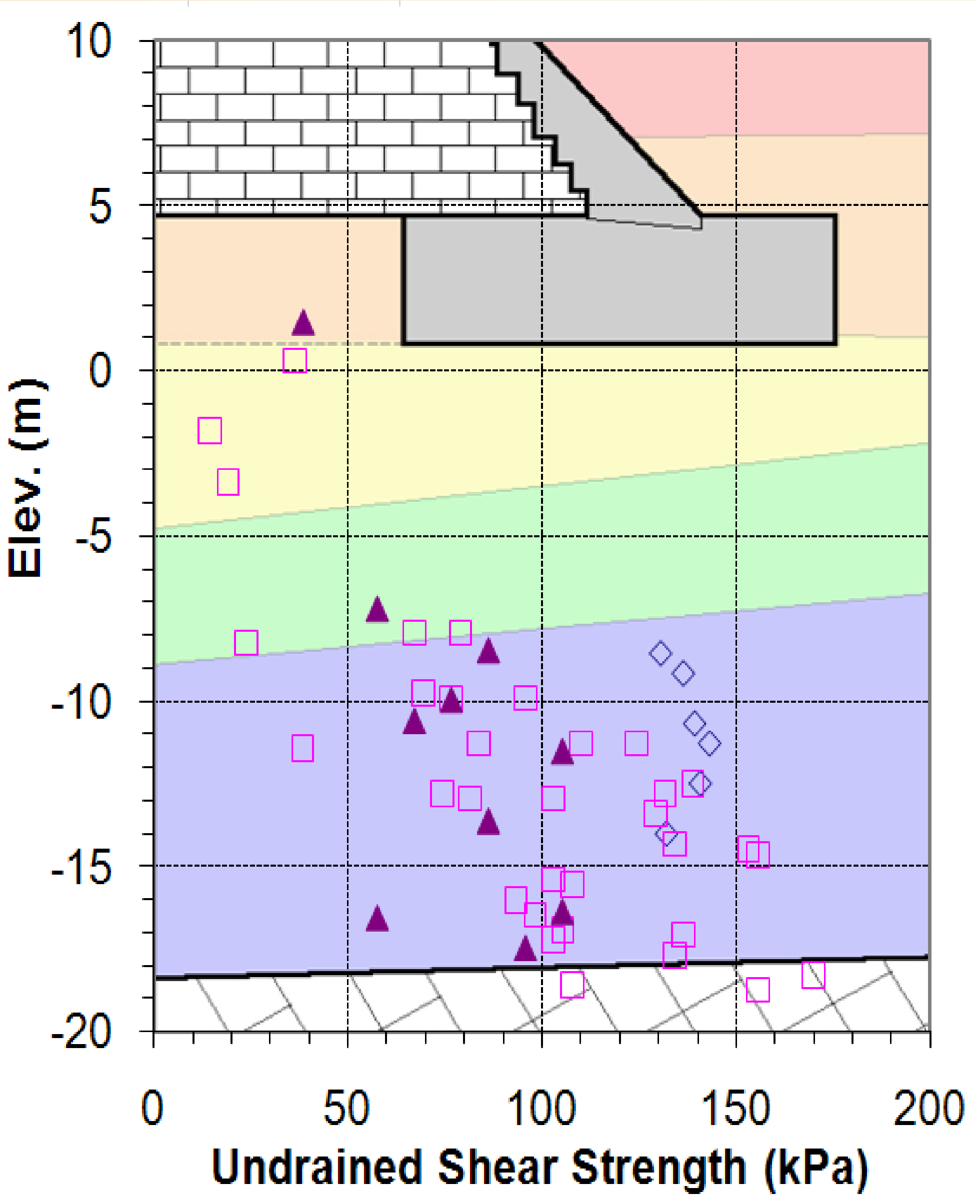
SOIL PROPERTIES

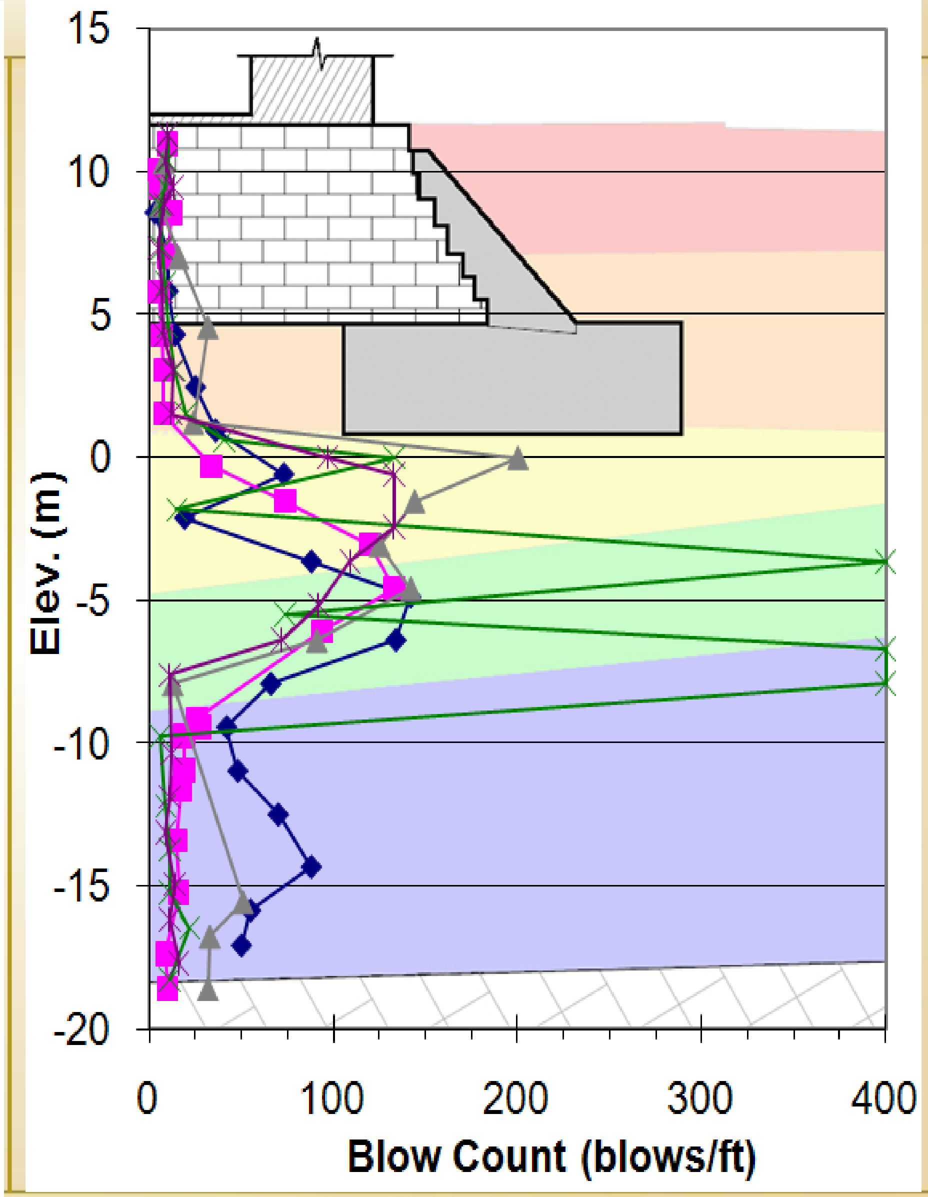




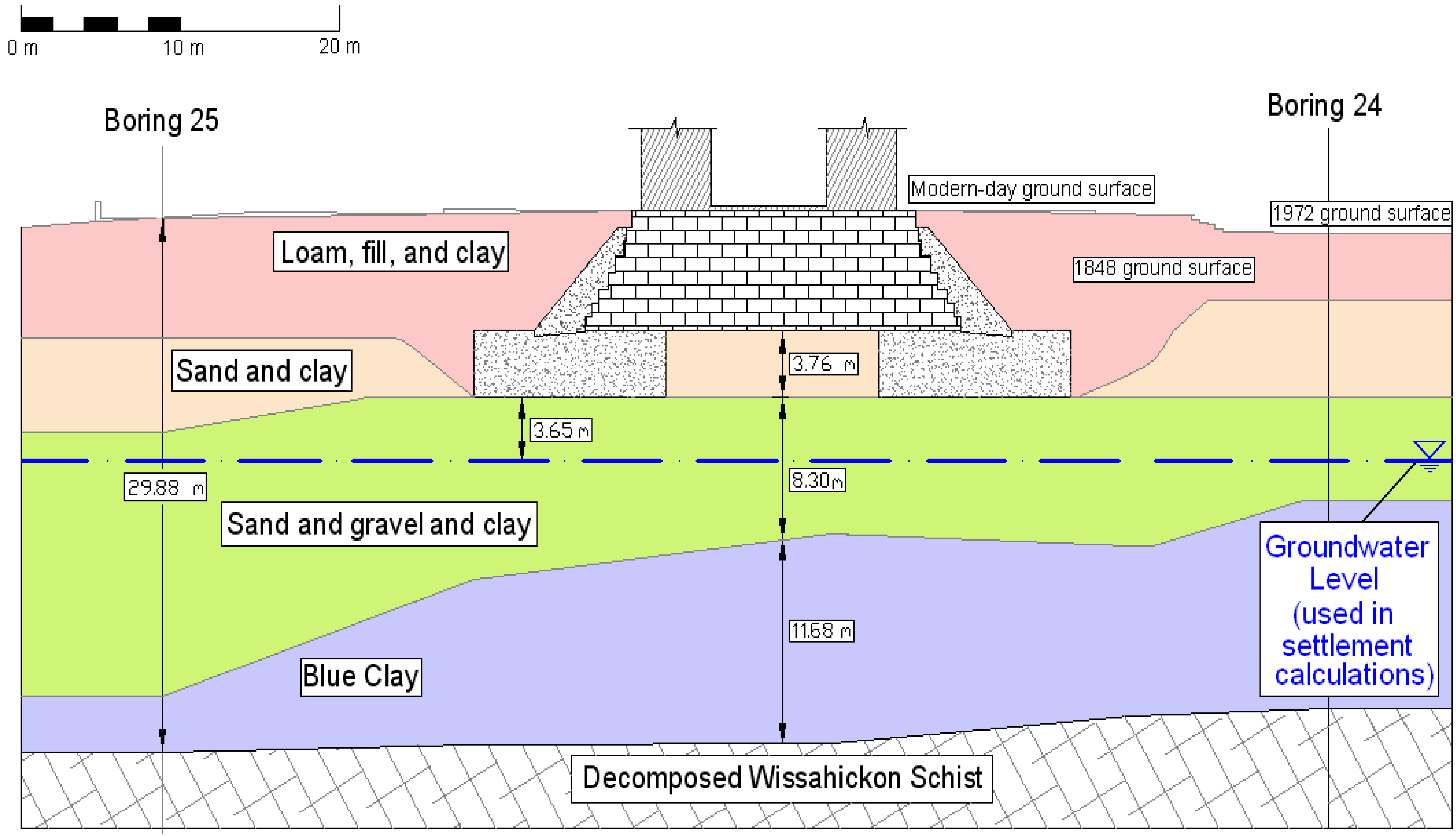
SOIL PROPERTIES

TEXAS A&M UNIVERSITY





BEARING CAPACITY



BEARING CAPACITY

- Actual Pressure under old foundation = 513 kPa
- Ultimate pressure P_u under old foundation (Clay)

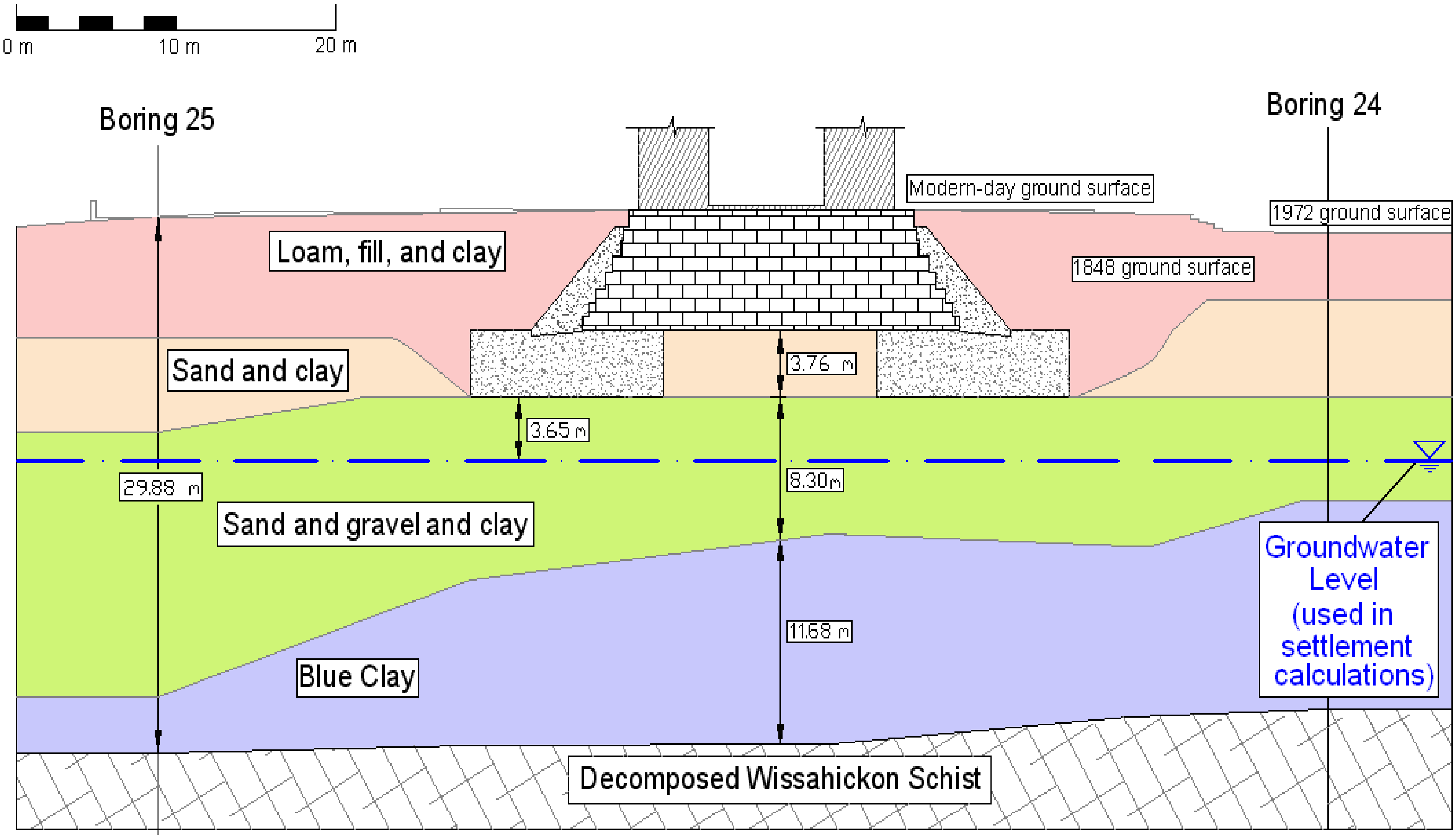
$$P_u = N_c S_u + \gamma D$$

  - S_u = 72 kPa (from N=12 bpf, Kulhawy and Mayne, 1990), D = 2.34 m (at time of maximum loading), N_c = 6.2 (square foundation)
  - Then P_u = 491 kPa
- Ultimate pressure P_u under old foundation (Sand) (Briaud and Gibbens, 1999):

$$P_u\left[kPa\right] = 75 \times N\left[\frac{blows}{ft}\right]$$

  - Blow count (N) = 12 bpf, Then P_u = 900 kPa
- FS = 0.96 – 1.75

BEARING CAPACITY



BEARING CAPACITY

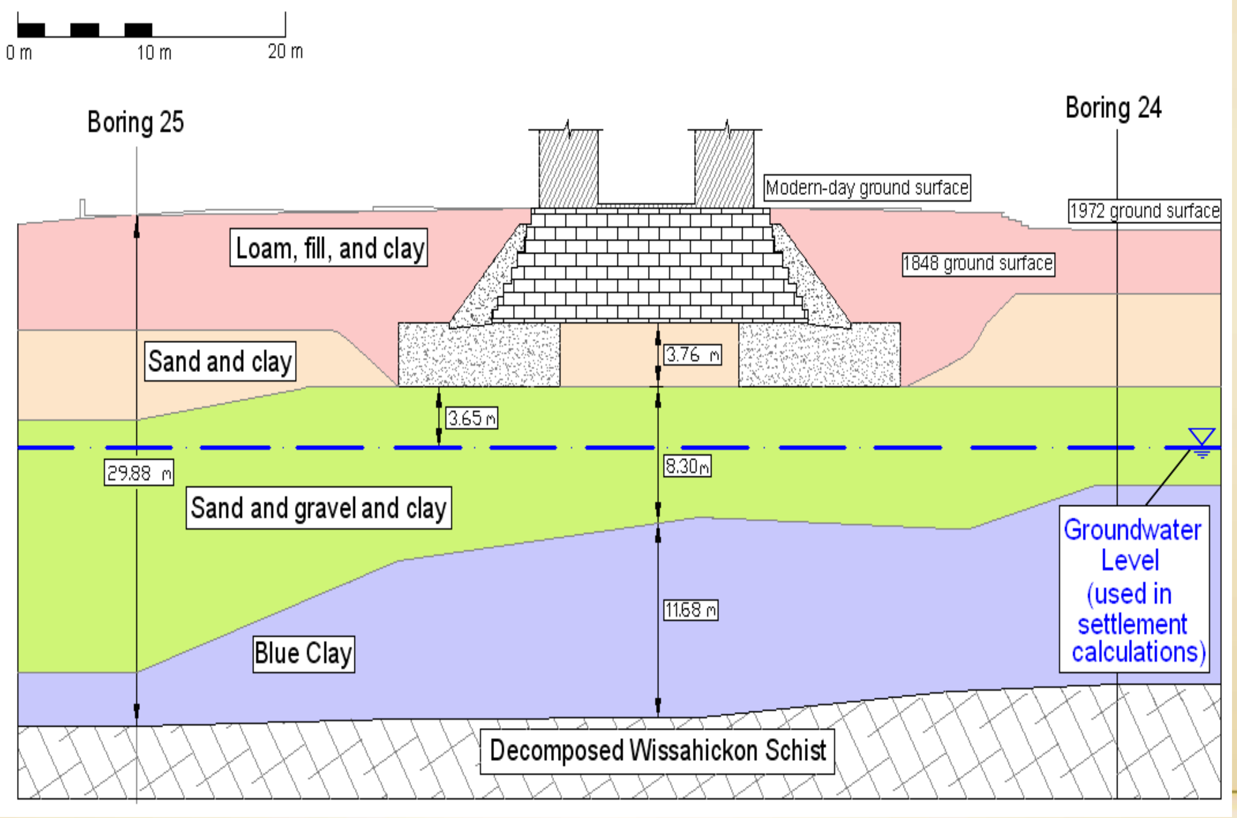
- Actual pressure at end of construction = 465 kPa
- Ultimate pressure P_u under new foundation:

$$P_u A_f = P_u(clay) A_f + \left(p_{inside} + p_{outside}\right) H \times k_o \sigma'_{ov} \tan\phi$$

  - A_f = area of the foundation
  - p_{inside} = inside perimeter of foundation
  - $p_{outside}$ = outside perimeter of foundation
  - H = thickness of sand layer
  - k_0 = coefficient of earth pressure at rest in sand layer
  - σ'_{ov} = vertical effective stress at middle of sand layer
  - Φ = effective stress friction angle of the sand layer
- Then P_u under the new foundation = 987 kPa
- Factor of safety = 2.4.

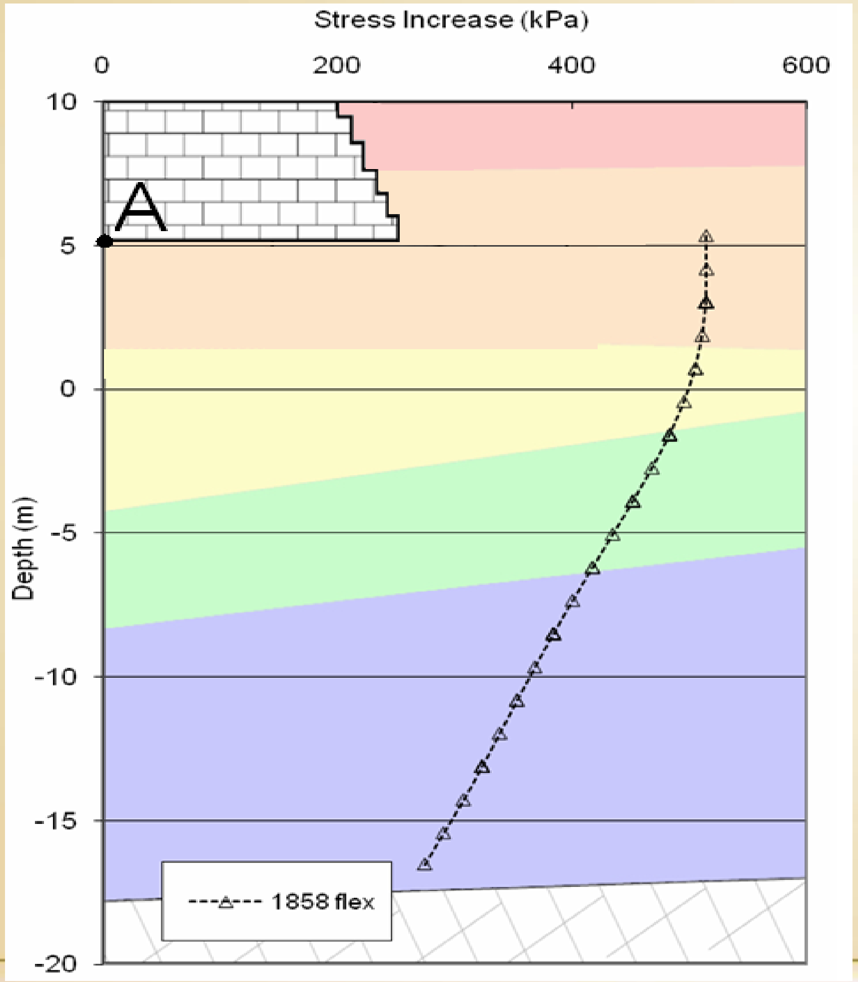
DEPTH OF INFLUENCE

In this case the depth of influence is set by the presence of the shallow bedrock at about 20 m depth

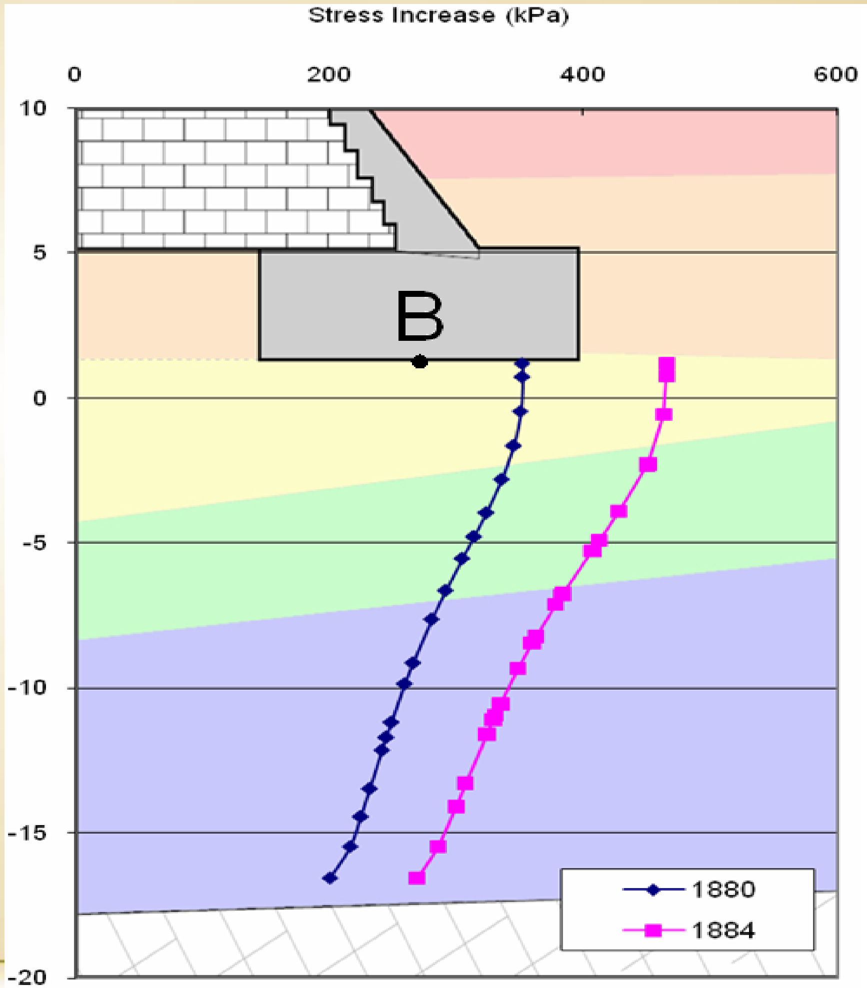


STRESS INCREASE WITH DEPTH BY 3D FEM (ABAQUS)

Old foundation
(After Phase 1)



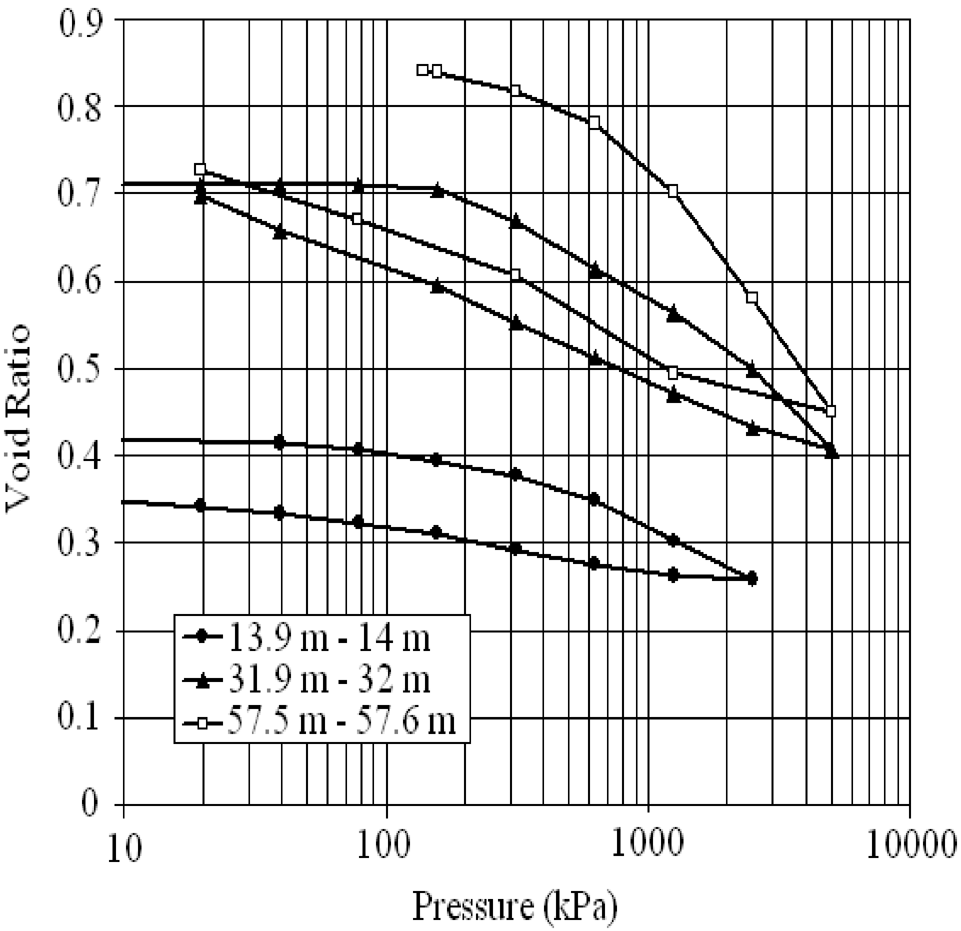
Underpinned foundation
(Before & after Phase 3)

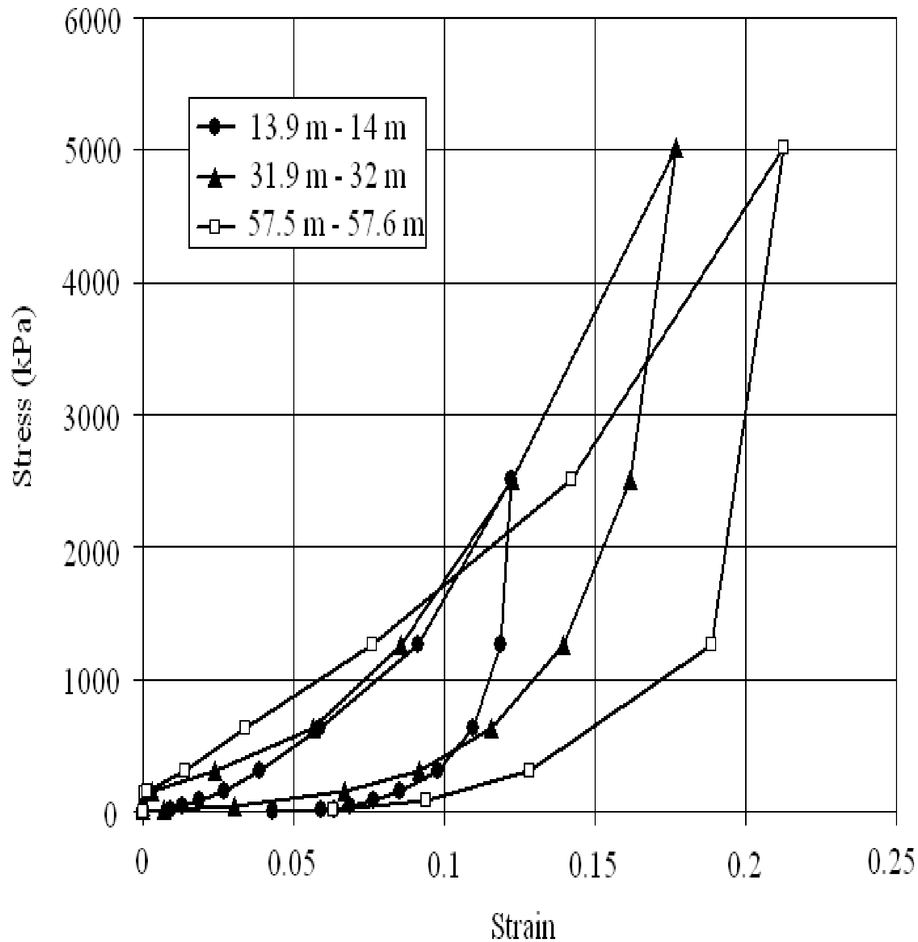


CONSOLIDATION CALCULATIONS

- Calculated settlement for:
  - Phase 1 (From 1948 to 1958)
  - Phase 2 (Underpinning of Monument)
  - Phase 3 (Completion of Monument)
- Three methods:
  - Curve method (Method a)
  - Equation method With Cr measured on initial loading curve (Method b)
  - Equation method With Cr measured on unload/reload curve (Method c)

CONSOLIDATION CURVE

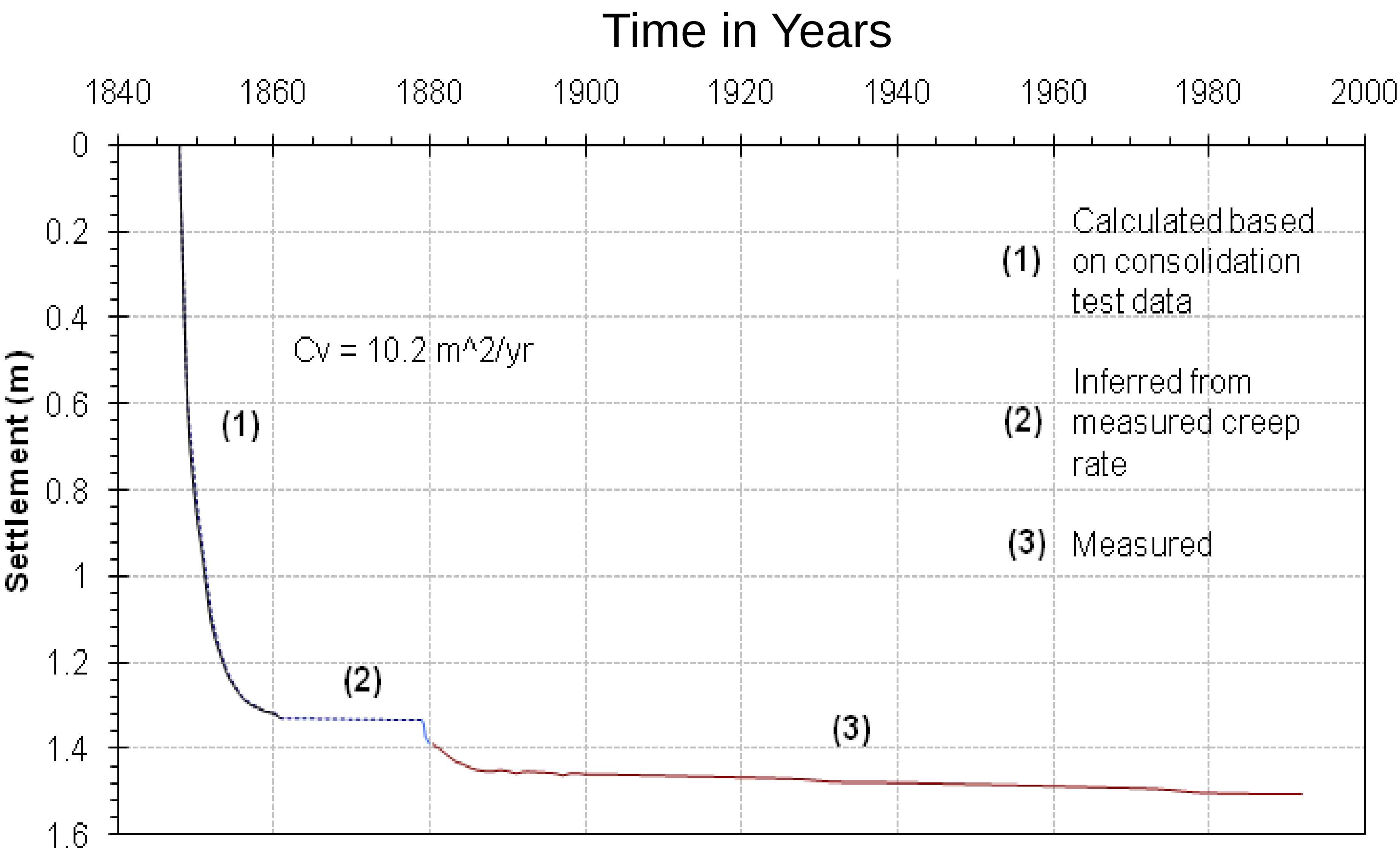




CONSOLIDATION SETTLEMENTS PREDICTED VS. MEASURED

Assumption Case	Settlement (m)		
	Sub-case		
	a	b	c
Phase 1 (calculated)	1.328	1.398	1.465
Phase 3 (calculated)	0.116	0.102	0.130
Phase 3 (measured)	0.119	0.119	0.119

RECONSTITUTED SETTLEMENT



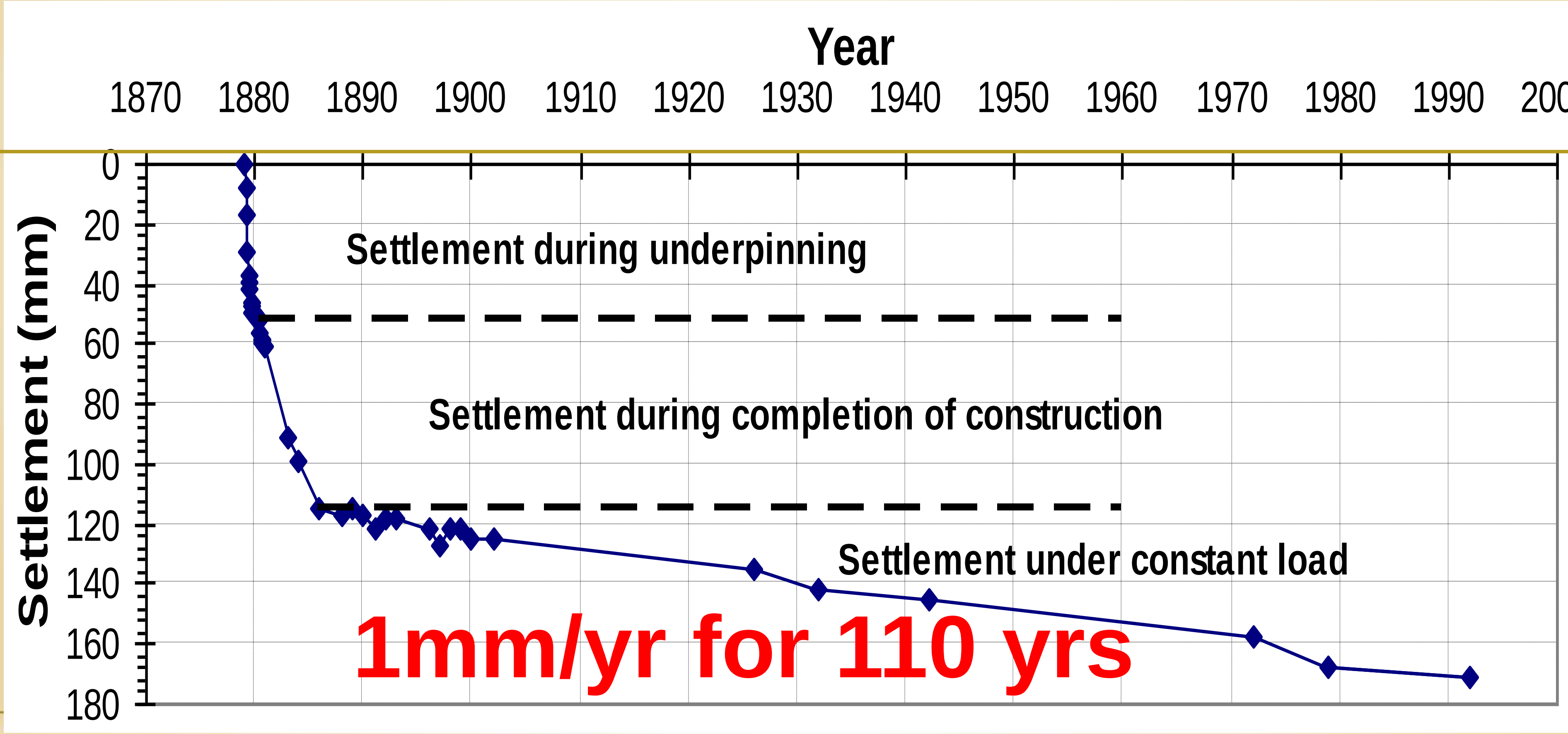
SETTLEMENT MONITORING

- Settlement was not measured during Phase 1
- Casey placed reference points at each corner of the top of the original foundation
- The benchmark used is the Meridian Stone which is marked by a bolt in the center of a square granite post set flush with the ground
- Settlement first measured in February 1879
- During underpinning, settlement readings for each corner were taken and recorded once daily, and since that time.

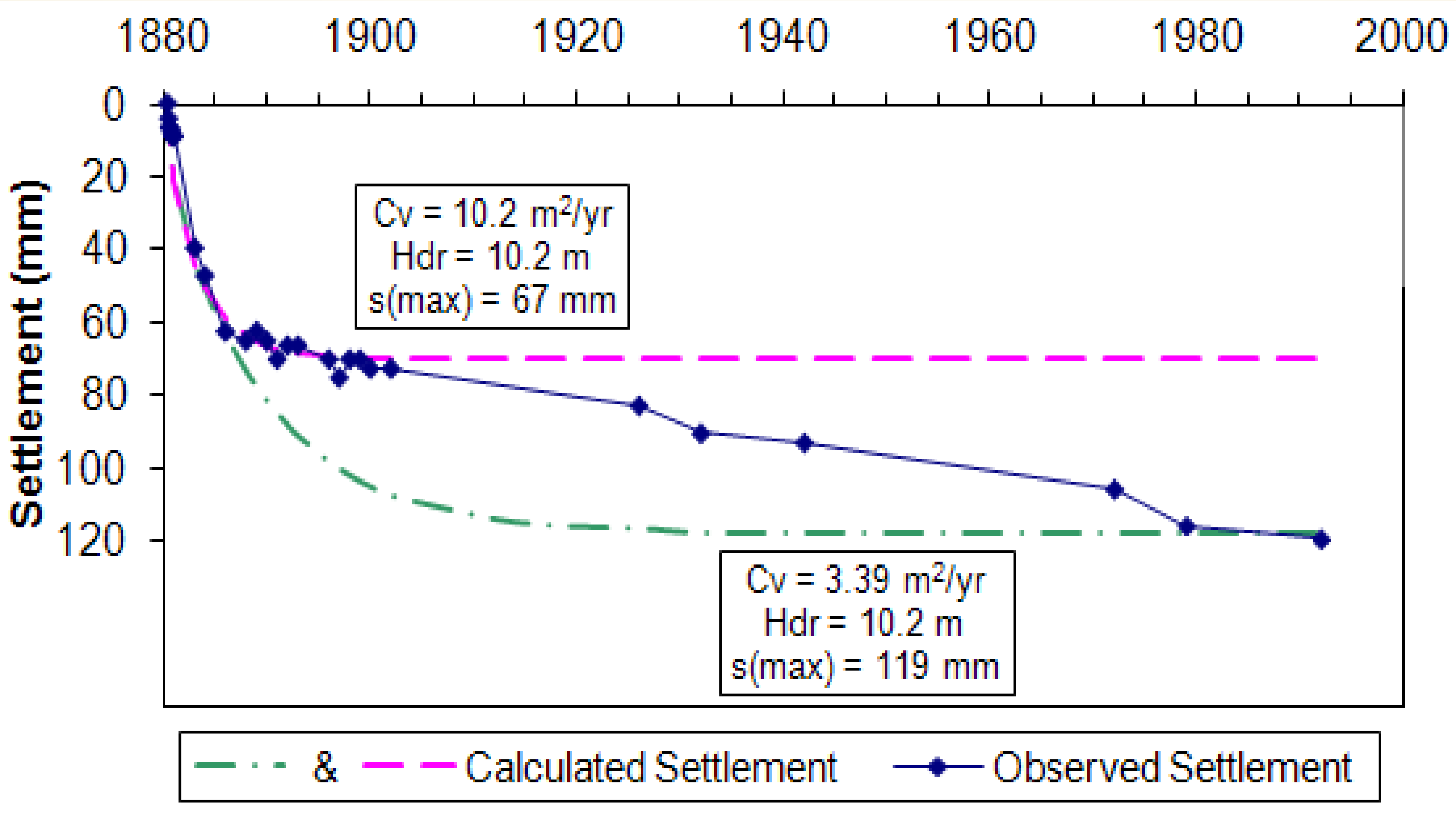
BENCHMARK IS THE MERIDIAN STONE AT THE WHITE HOUSE

MEASURED SETTLEMENT

- Settlement after underpinning = 52 mm
- Settlement after completion = 115 mm
- Settlement after last reading (1992) = 170 mm



Measured vs. Calculated Settlement



- Drainage length (H_{dr}) = 10.2 m (one-way)
- C_v = 10.2 m^2/yr (average), C_v = 3.39 m^2/yr (minimum)

$$T = \frac{t \cdot c_v}{H_{dr}^2}$$

CONCLUSIONS

- After Phase 1, the pressure was close to the ultimate pressure and the settlement was 1.4 m
- Underpinning saved the monument by reducing the net pressure on the soil and increasing the ultimate bearing capacity (FS = 2.4)
- The calculated settlement for Phase 2 and 3 matched well the measured settlement (?!)
- Creep settlement has been consistent at less than 1mm/year for 110 years.

CONCLUSIONS

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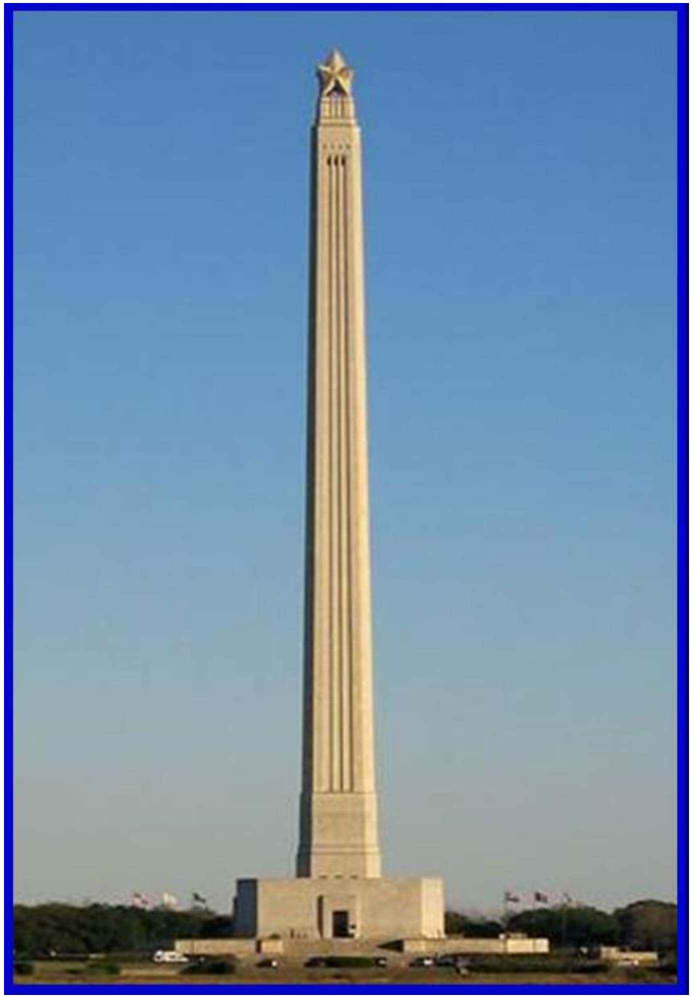
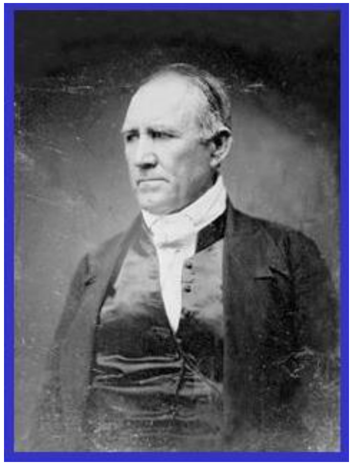
- Read the consolidation curve directly for settlement calculation
- Plot the consolidation curve as a stress strain curve.
- Beware of the unload-reload loop as the slope depends on the stress release amplitude

The San Jacinto Monument Case History



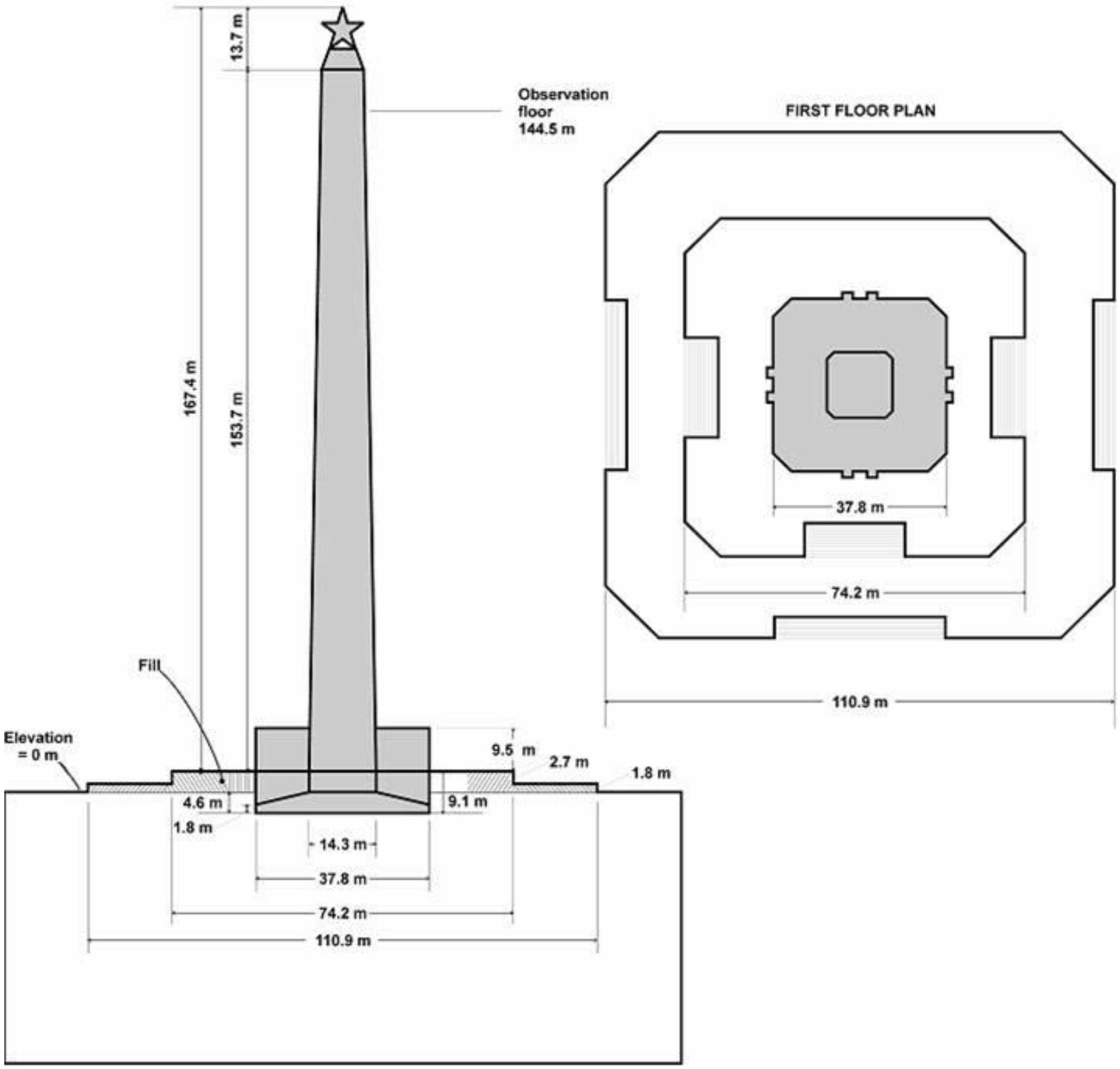
Picture obtained from http://www.laanba.net/photoblog/ January05/sanjacinto.jpg



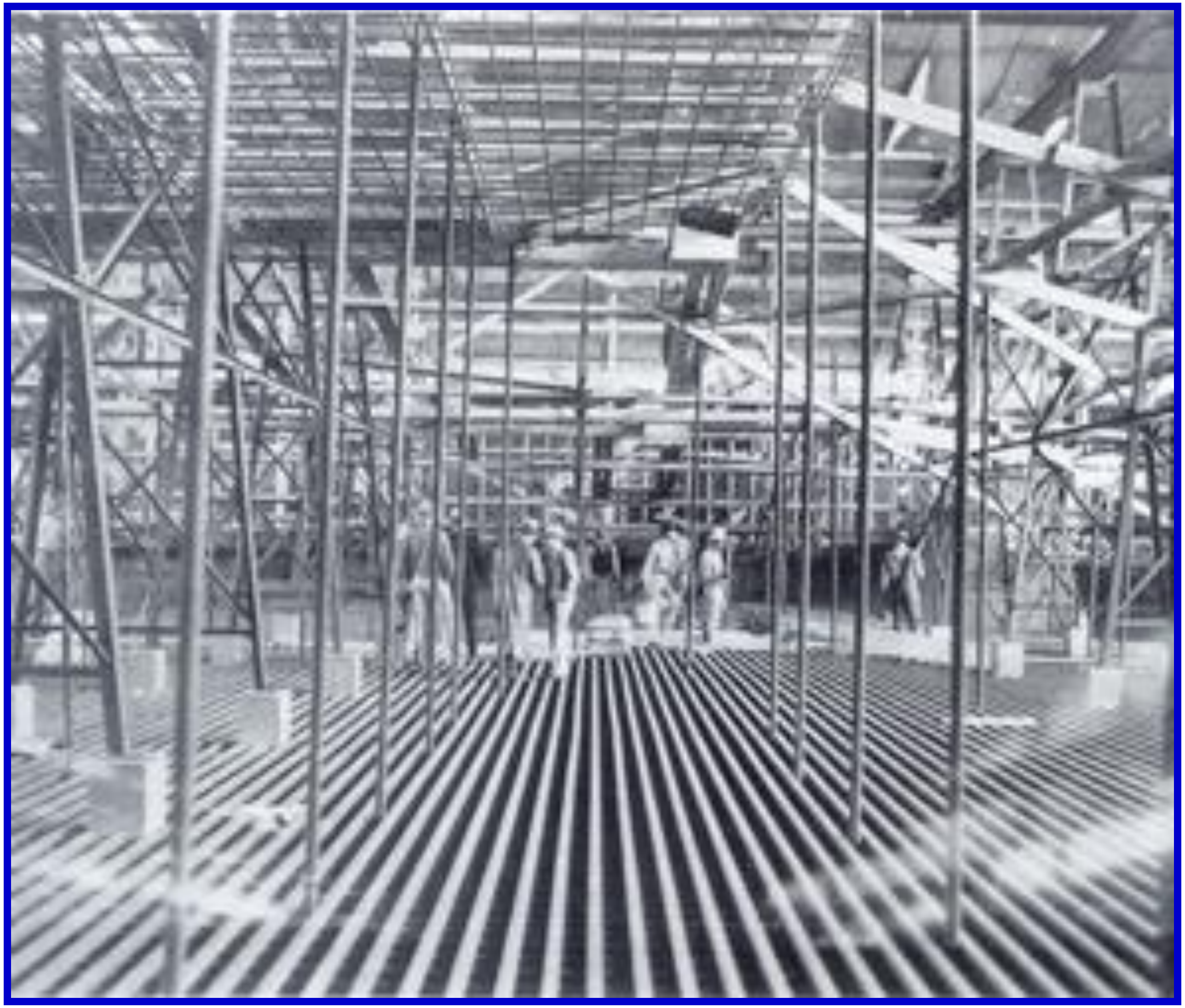
History

- March 2, 1836:
  - Texas declares its independence from Mexico
- March 6, 1836: The Battle of The Alamo
  - Mexico (Santa Anna) defeats Texas
- April 21, 1836: The Battle of San Jacinto
  - Texas (Sam Houston) defeats Mexico

Structural Dimensions



Construction

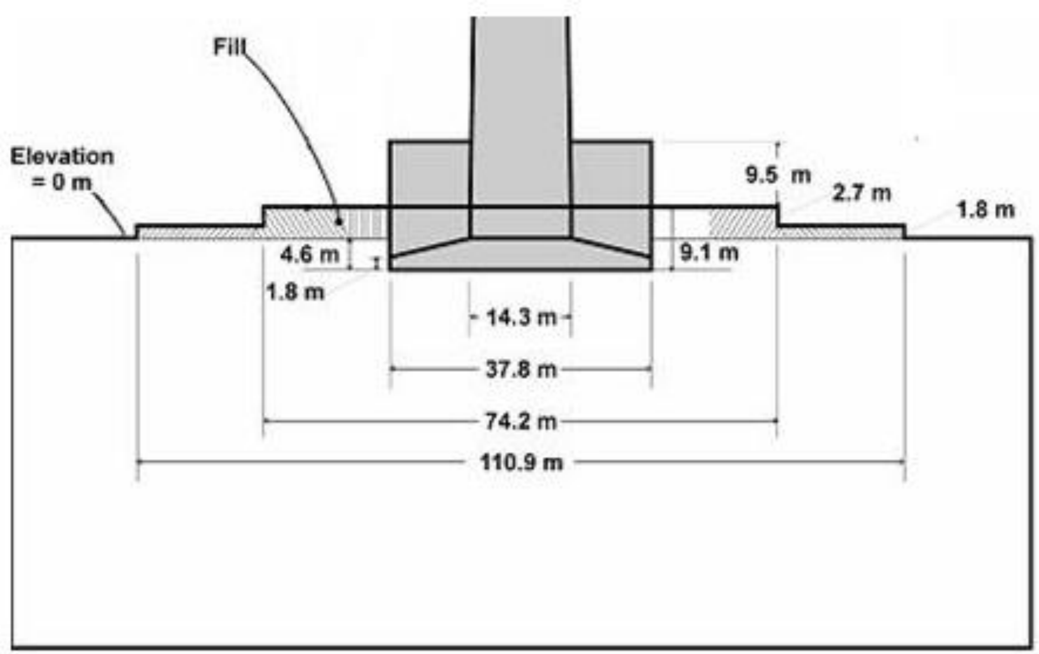


Reinforcement in the Foundation
(Bullen, 1938)

Construction

Loading

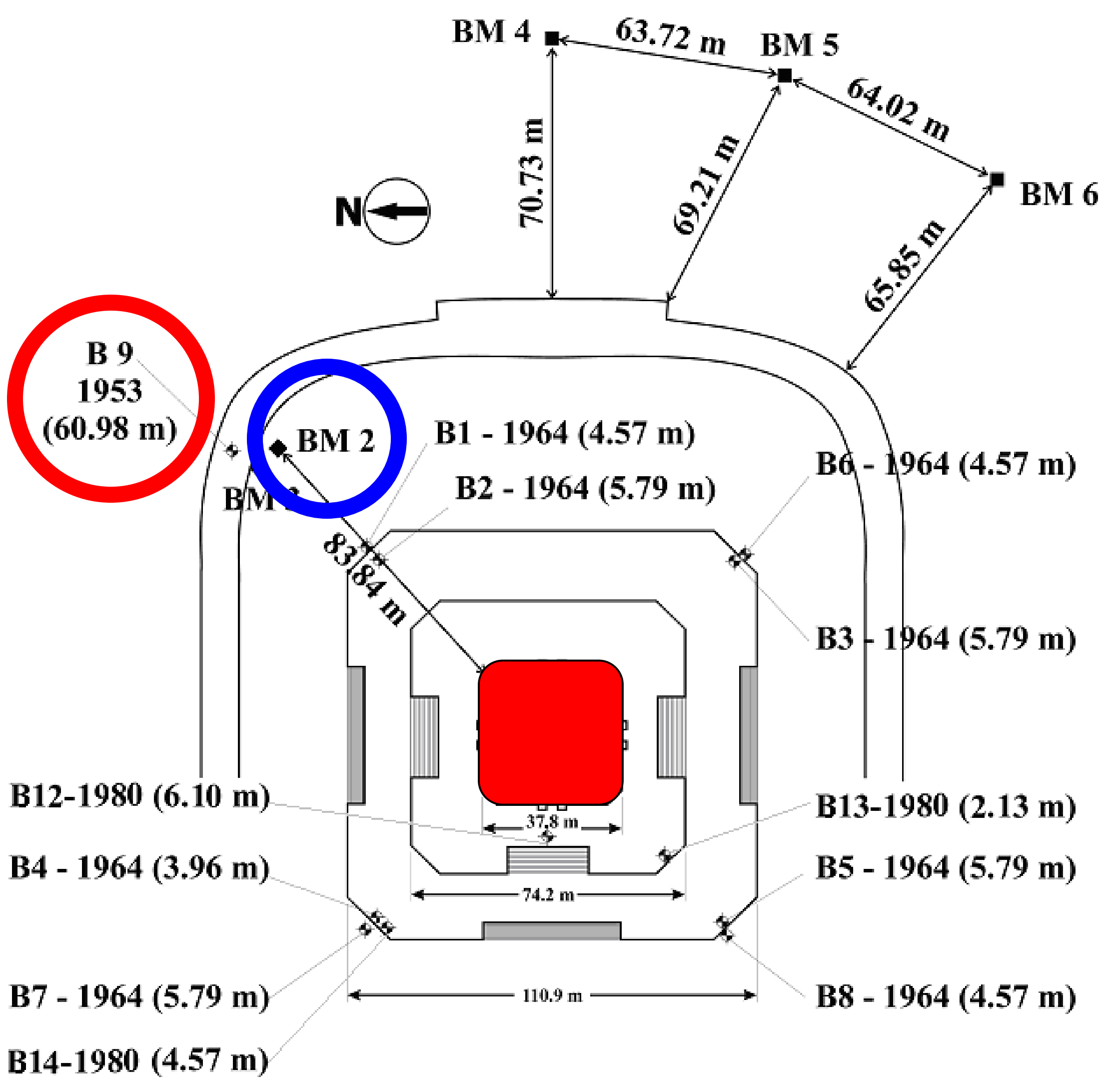
- Gross pressure = 224 kPa
- Max pressure (dead + wind) = 273 kPa
- Excavation = -83 kPa
- Net pressure = 141 kPa
- Net pressure after mat poured = 10 kPa
- Pressure from Terraces = 34 kPa and 85 kPa

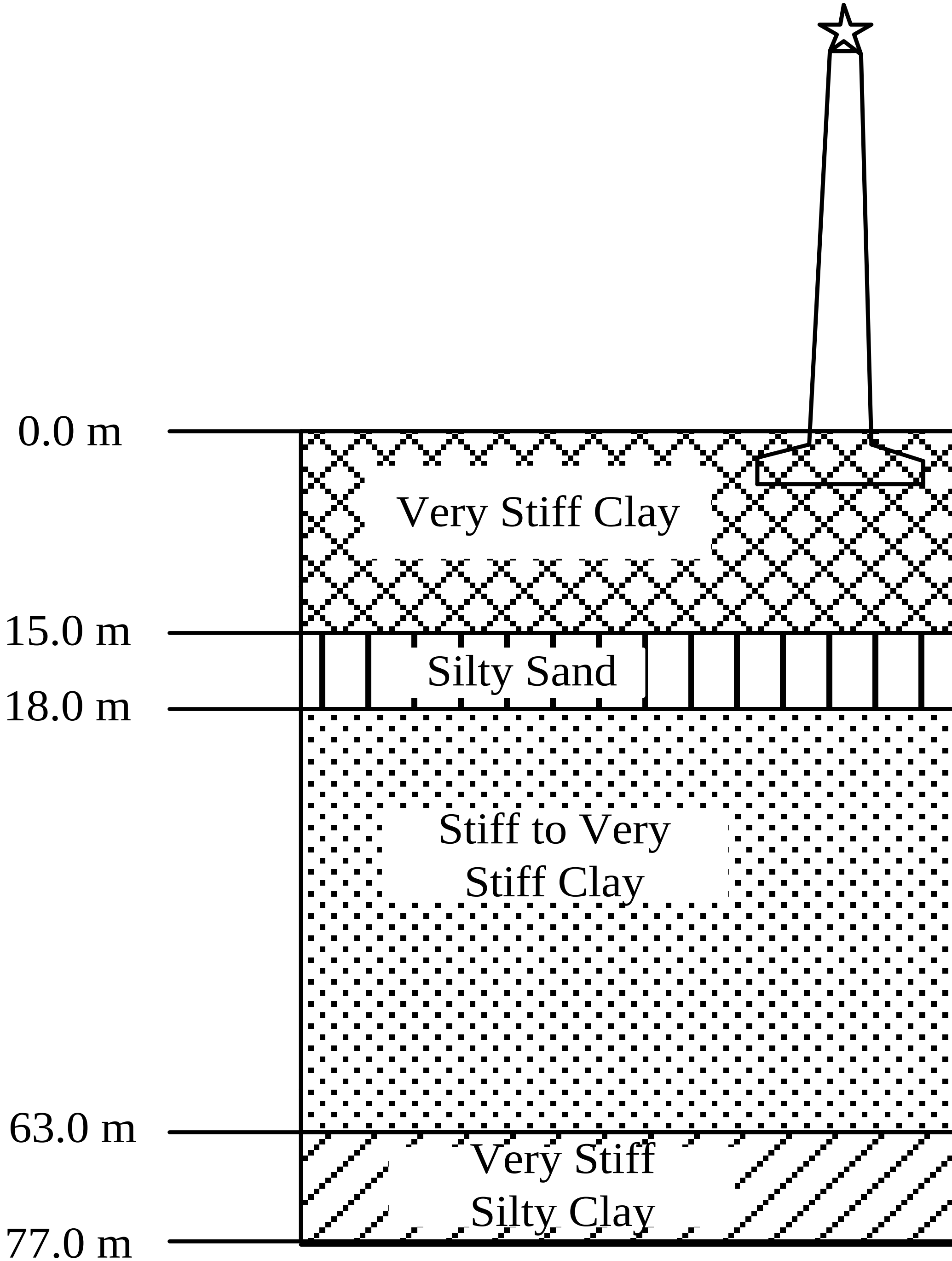


Soil Borings

Boring Date	No. of Borings	Boring Depth (m)	Company	Comments
1936	1	**6.1**	Layne Texas	No. and location unknown
1938	1	**198.2**	Unknown	Location unknown, water well
1948	1	**44.2**	Unknown	Location unknown
1953	1	**61**	Unknown	Likely used by Dawson for teaching purposes
1964	8	**4.5 to 6.1**	Golemon & Rolfe	For repairs to the Monument
1976	13	**3 to 12**	Murillo Eng.	For new construction around the reflection pool
1980	3	**2.1 to 6.1**	McClelland	Study of the movements
Unknown (>1946)	1	**47.6**	McClelland	Unknown date and location

Location of Soil Borings

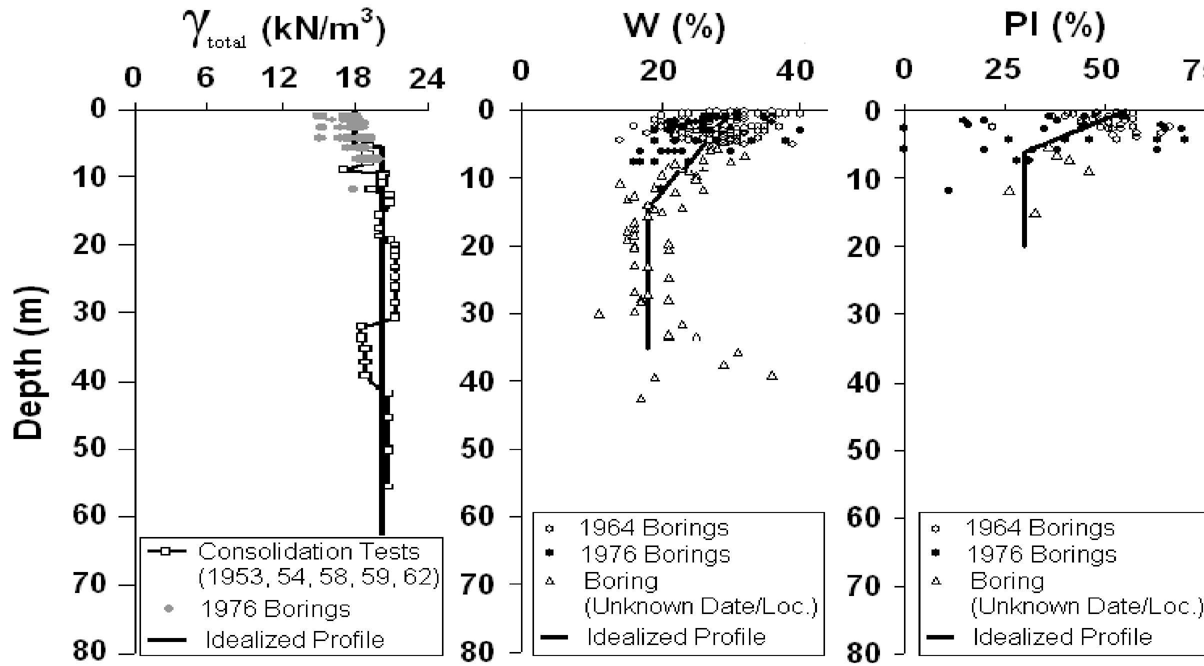




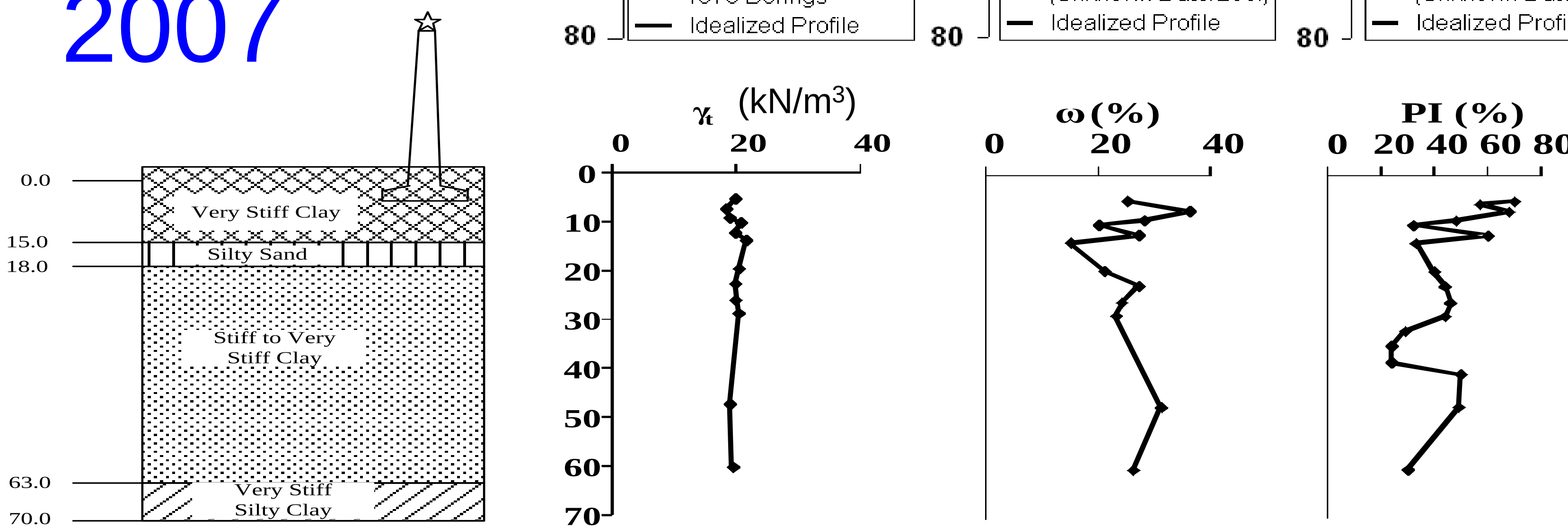
Depth (m)	Soil Type
0-7.5	Very Stiff Clay, red and gray
7.5-11	Very Stiff Clay, red and gray
11-15	Very Stiff Clay, red and gray
15-17	Silty Sand, Very Dense
17-18	Silty Sand Very Dense
18-20	Very Stiff Clay
20-23	Very Stiff Clay
23-26	Very Stiff Clay, ligh gray and red
26-28	Clay with Ferrous nodules
28-31	Clay, light gray and tan
31-38	Silty Clay, brown and gray
38-40	Very Stiff Clay, red and gray
40-47	Very Stiff Clay, red and gray
47-53	Very Stiff Clay, red and gray
53-62	Silty Clay with gray sand
62-64	Silty Clay with clay stones
64-75	Stiff Silty Clay, gray
75-77	Stiff Silty Clay, gray

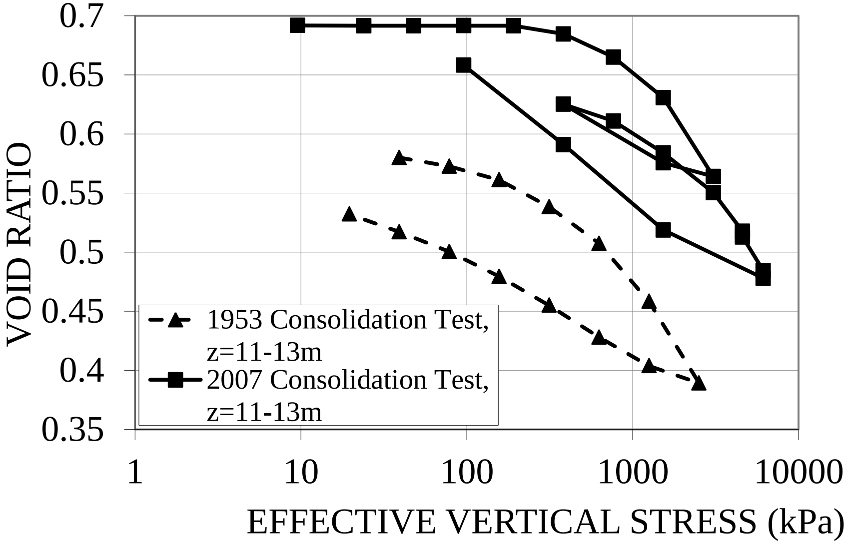
Soil Index Properties

1953

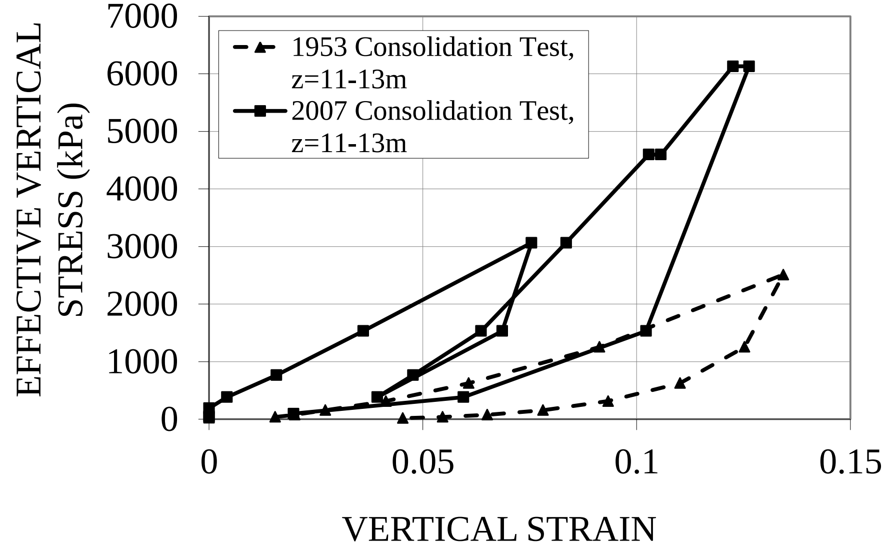


2007

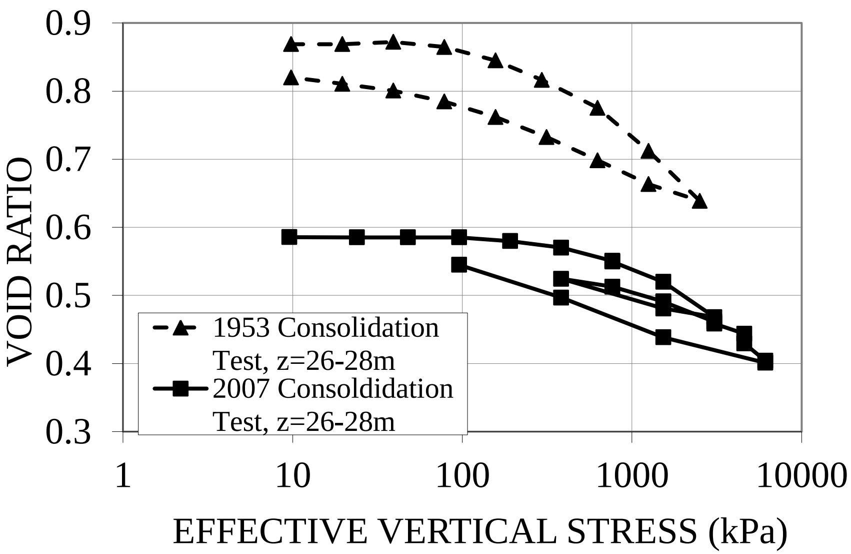




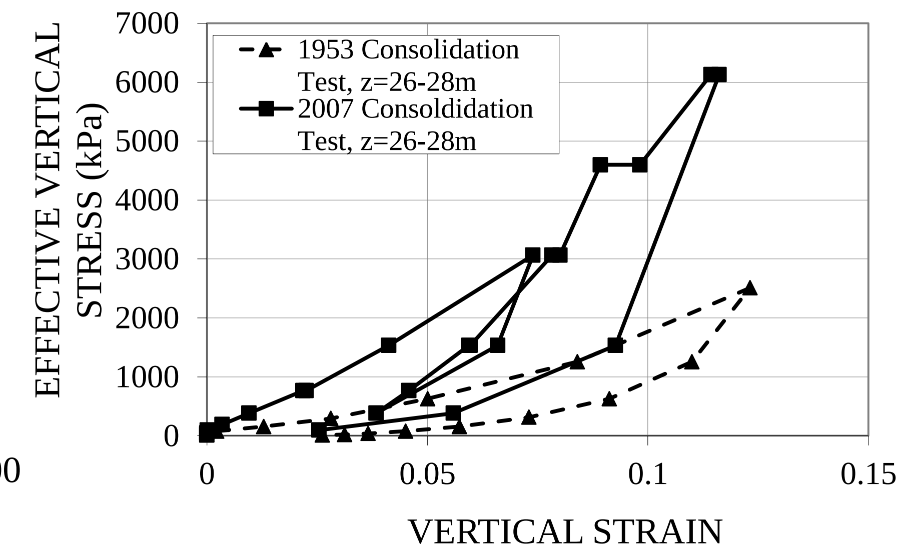
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
VOID RATIO
1
10
100
1000
10000
EFFECTIVE VERTICAL STRESS (kPa)
1953 Consolidation Test, z=11-13m
2007 Consolidation Test, z=11-13m



7000
6000
5000
4000
3000
2000
1000
0
EFFECTIVE VERTICAL STRESS (kPa)
0
0.05
0.1
0.15
VERTICAL STRAIN
1953 Consolidation Test, z=11-13m
2007 Consolidation Test, z=11-13m

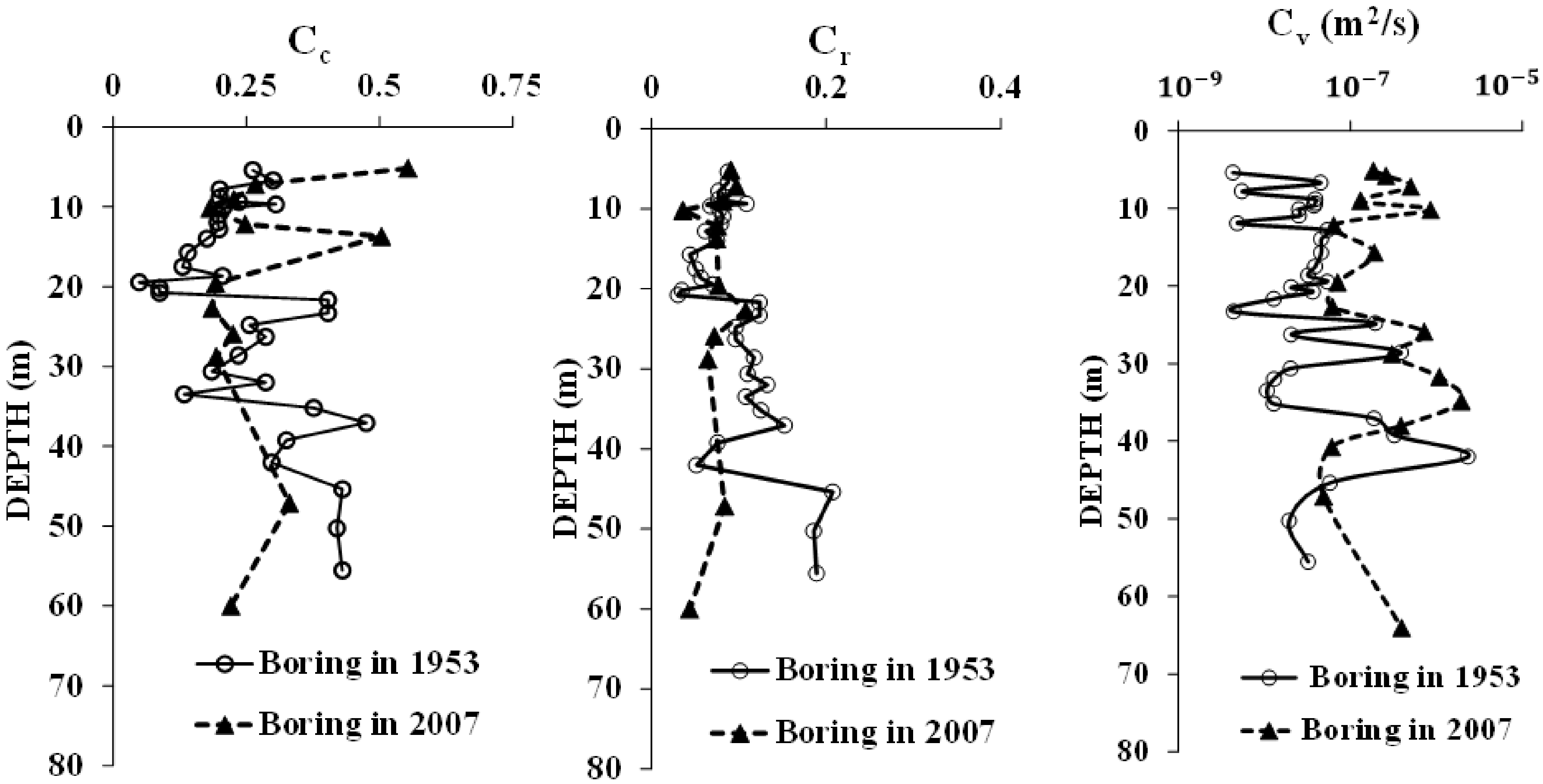


0.9
0.8
0.7
0.6
0.5
0.4
0.3
VOID RATIO
1
10
100
1000
10000
EFFECTIVE VERTICAL STRESS (kPa)
1953 Consolidation Test, z=26-28m
2007 Consoldidation Test, z=26-28m

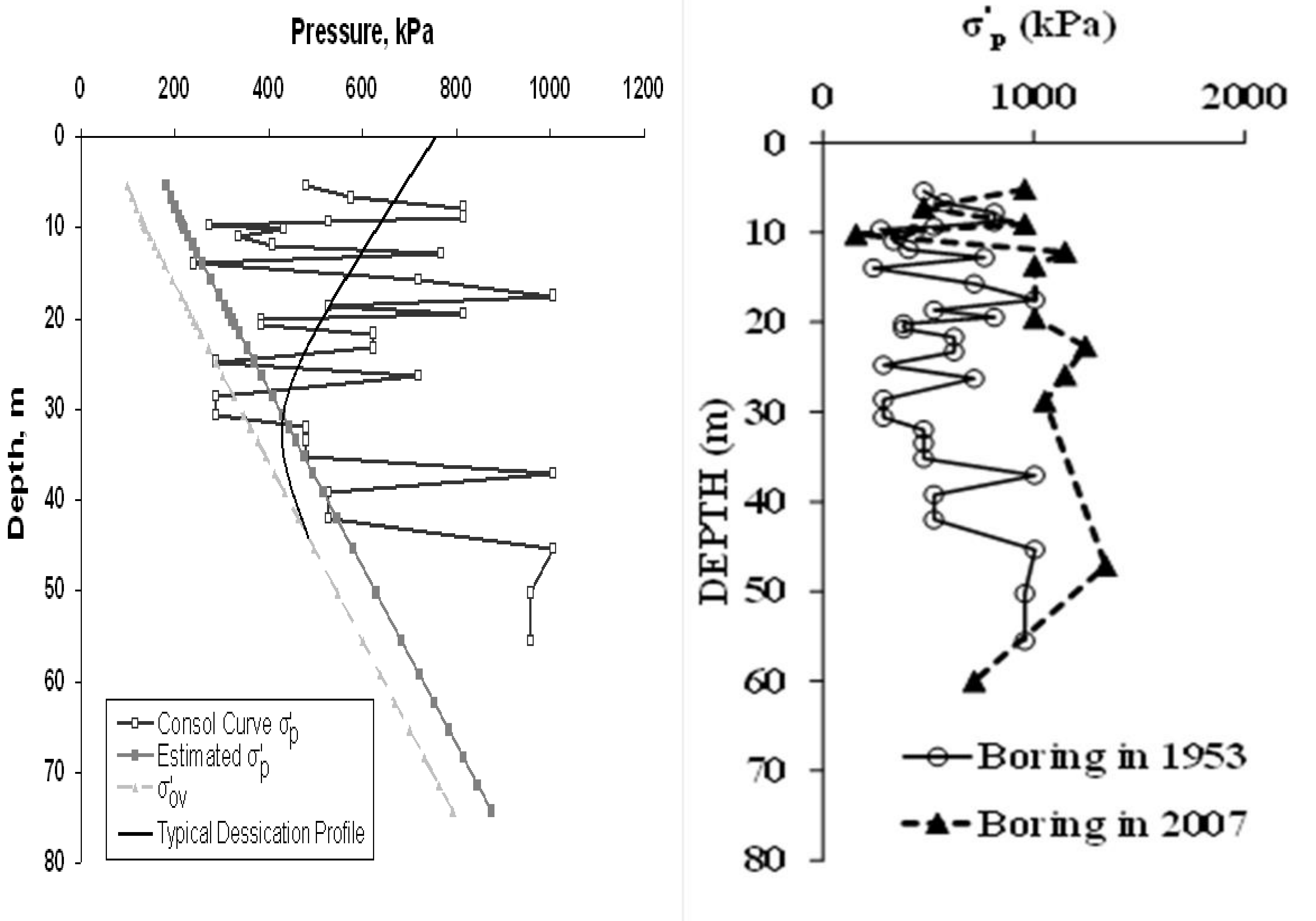


7000
6000
5000
4000
3000
2000
1000
0
EFFECTIVE VERTICAL STRESS (kPa)
0
0.05
0.1
0.15
VERTICAL STRAIN
1953 Consolidation Test, z=26-28m
2007 Consoldidation Test, z=26-28m

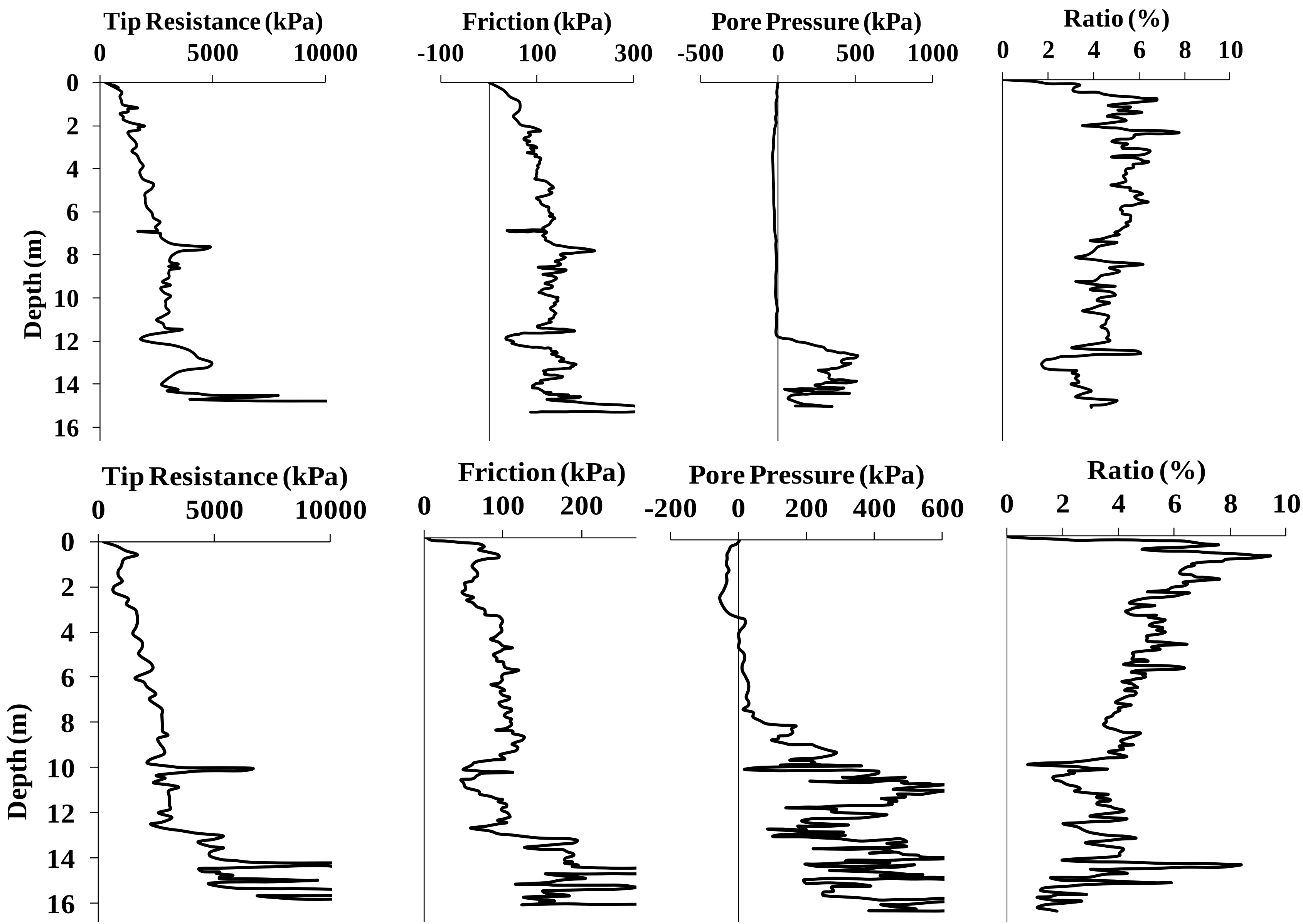
Consolidation Characteristics



Stress History

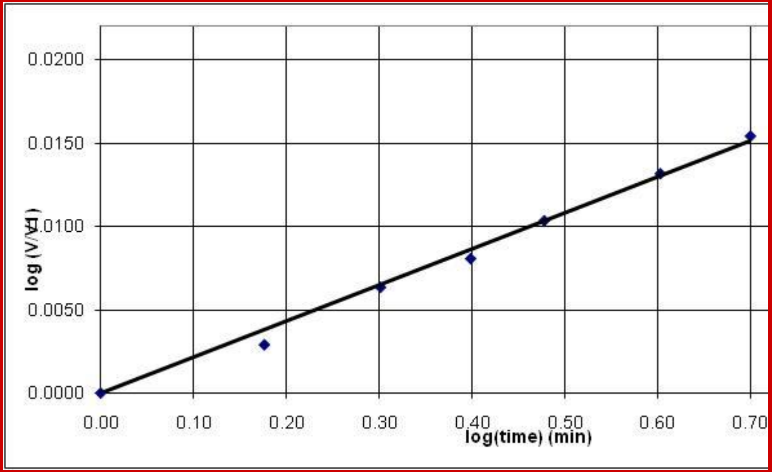


Cone Penetrometer Results



Pressuremeter

P_L=2.7 MPa, P_y=1.6 Mpa, E_0=54 MPa
E_r=145 MPa, n=0.022



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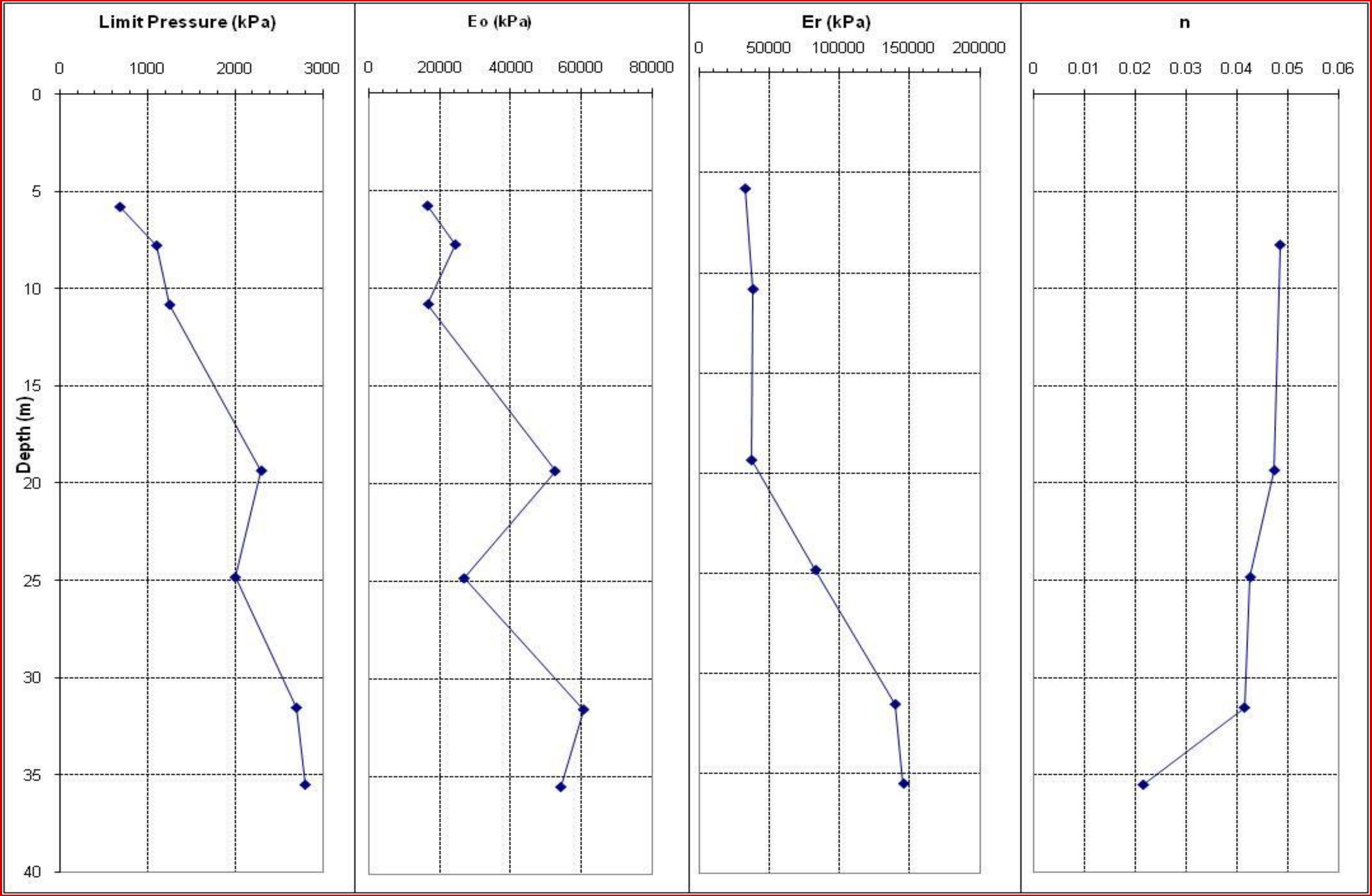
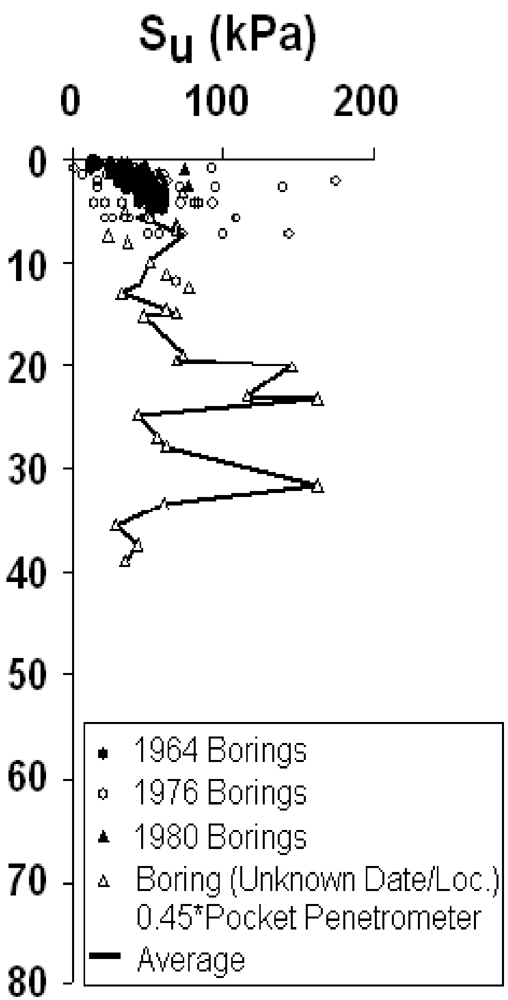
Pressuremeter

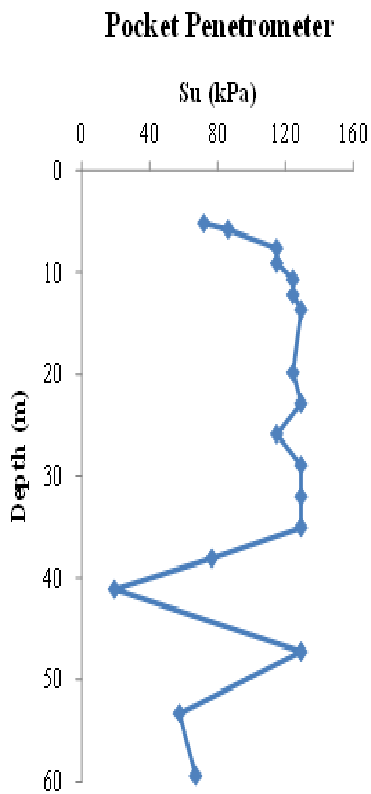


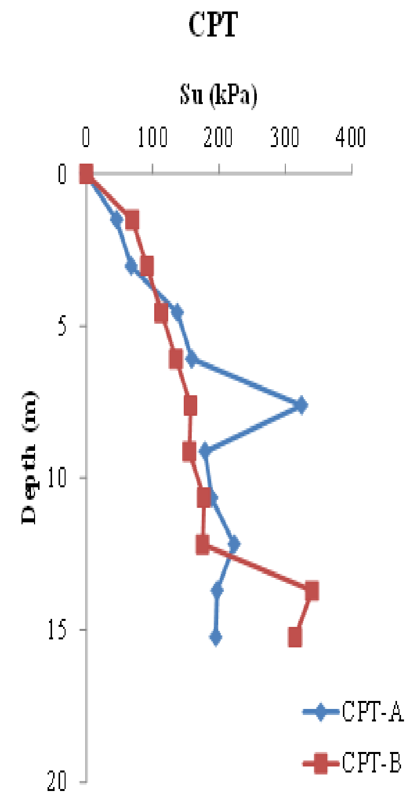
Undrained Shear Strength

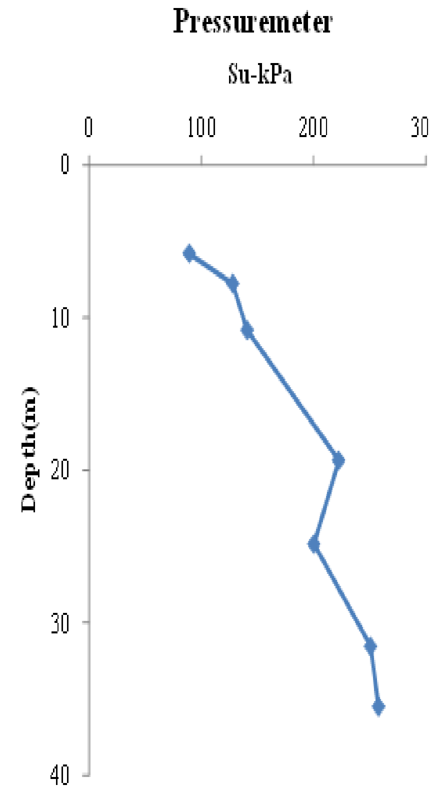
1953



2007







Ultimate Bearing Capacity

P_L = 680 kPa at 5 m depth

S_u = 100 kPa at shallow depth

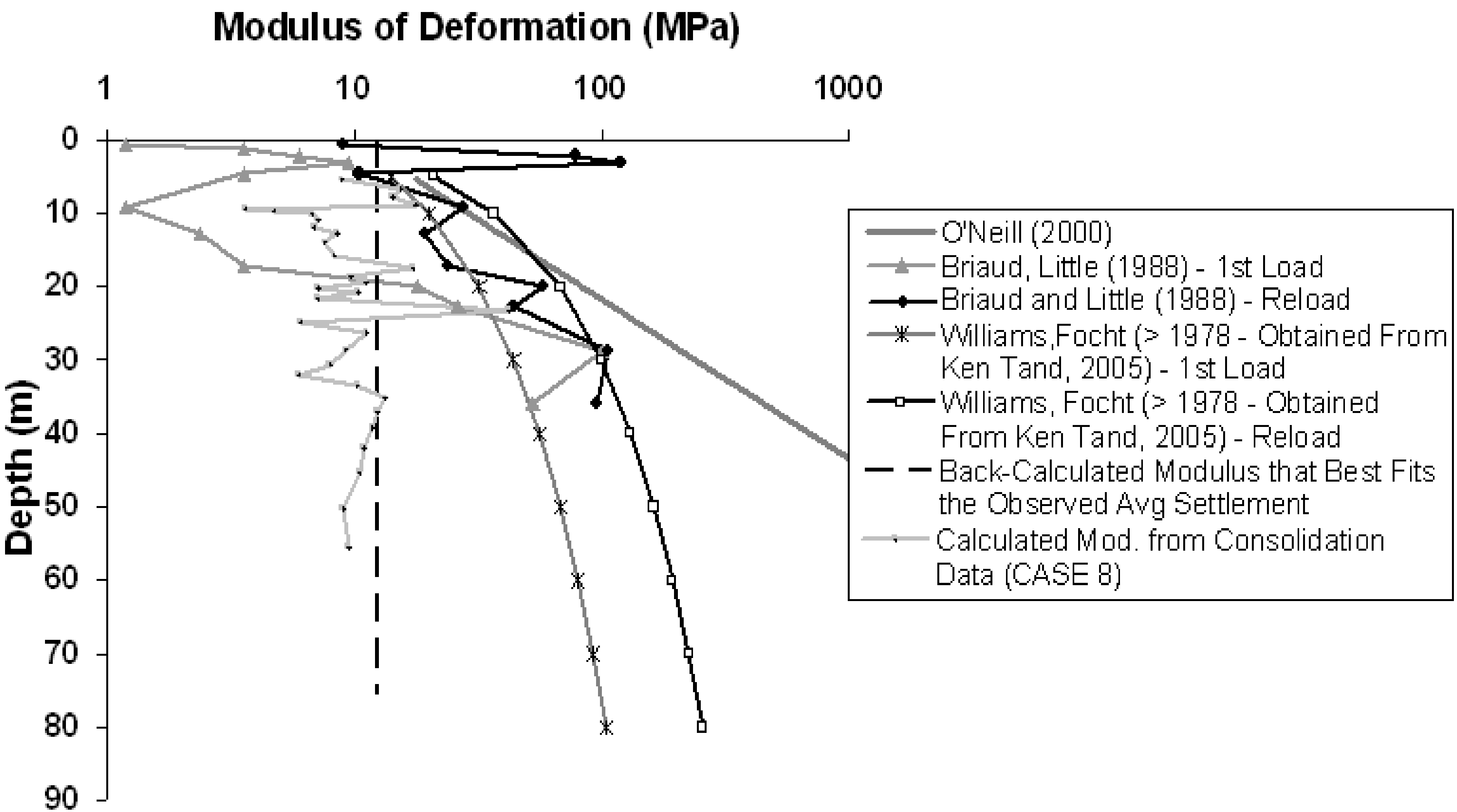
Total pressure at 5 m = 224 kPa

Net pressure at 5 m = 141 kPa

ULTIMATE BEARING CAPACITY

Test Method	Bearing Capacity (kPa)	F.S (Dead Load)	F.S (Hurricane + Dead Load)
S_U from Borings (Skempton, 1951)	721	3.22	2.64
CPT (Tand et al, 1986)	900	4.02	3.3
CPT (AFNOR-Frank 2013)	870	3.89	3.19
PMT (AFNOR-Frank 2013)	935	4.18	3.43

Modulus of Elasticity



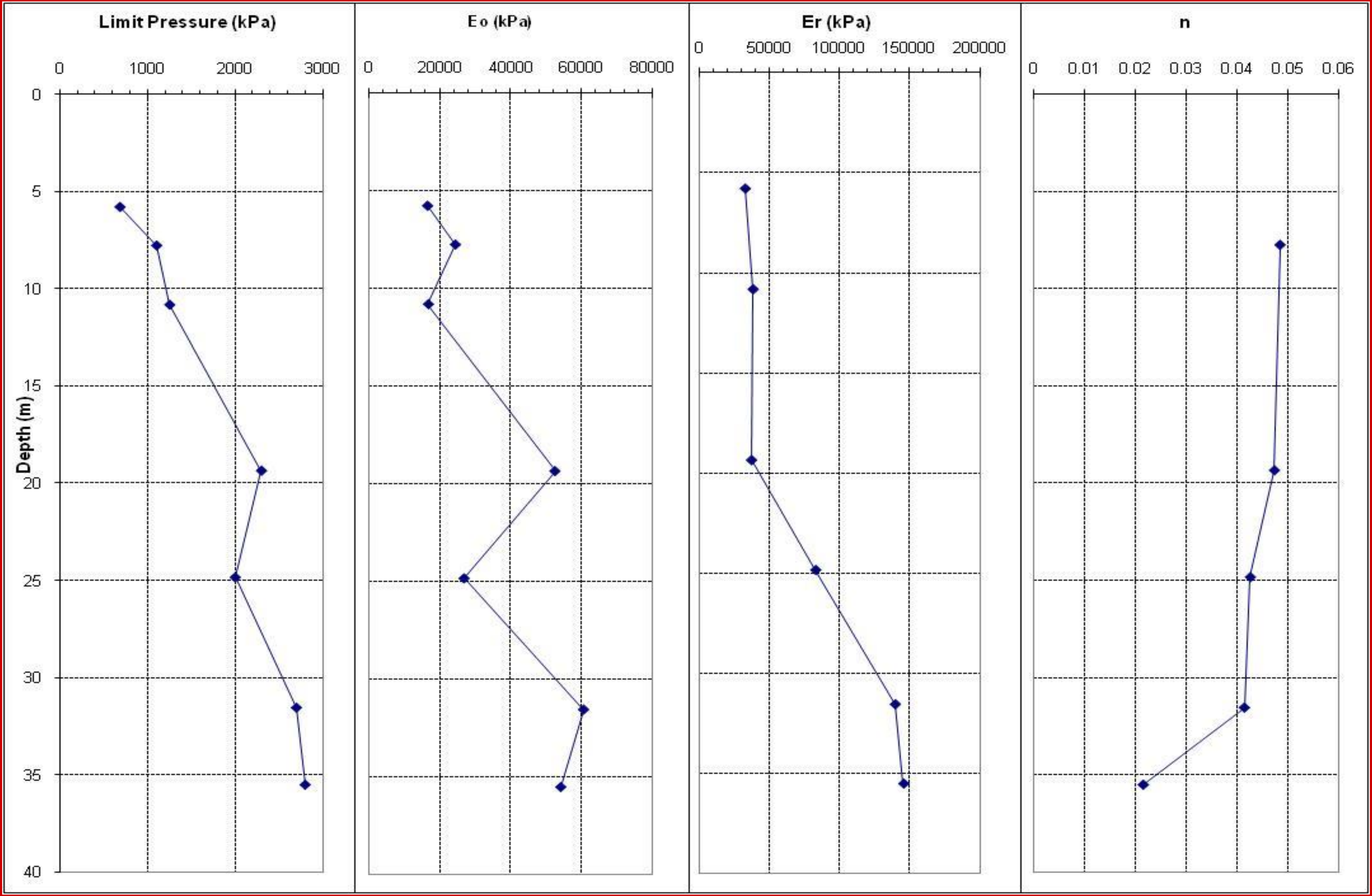
Modulus of Elasticity

- Using the elastic settlement equation,

  $$s = 0.88(1-v^2)pB/E$$

  the Modulus (E) at the site was back-calculated to be 12.3 MPa based on the last known settlement observation (s) of 0.329 m.
  - $v = 0.35$
  - $p = 138.9$ kPa (net pressure)
  - $B = 37.8$ m

Pressuremeter



Elastic Settlement

E_0 = 30 Mpa, B = 38 m, p = 141 kPa, γ = 0.35

$S(t_0) = 0.88(1 – 0.35^2)x141x38/30000 =$ 138 mm

Long Term Settlement

$s(t)/s(t_o) = (t/t_o)^n$

$s(t_o)$ = 138 mm, t = 70 yrs, t_o = 5 min, n = 0.045

S(70 years) = 138 (70 x 365 x 24 x 60 / 5) $^{0.045}$

S(70 years) = 325 mm

Modulus of Subgrade Reaction

- $k = p/s$
- Using the elastic settlement equation,

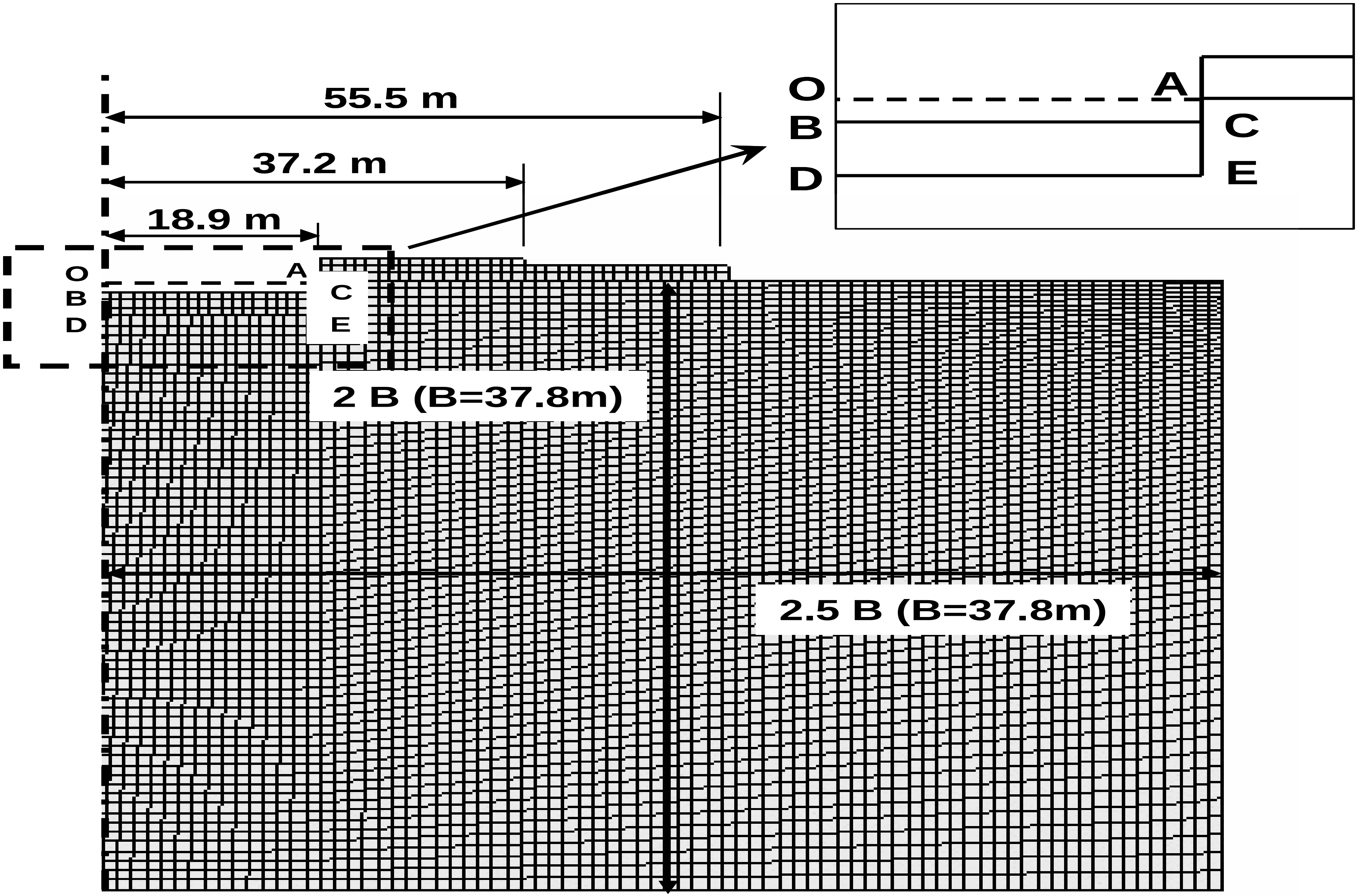
$$s = 0.88(1-v^2)pB/E$$

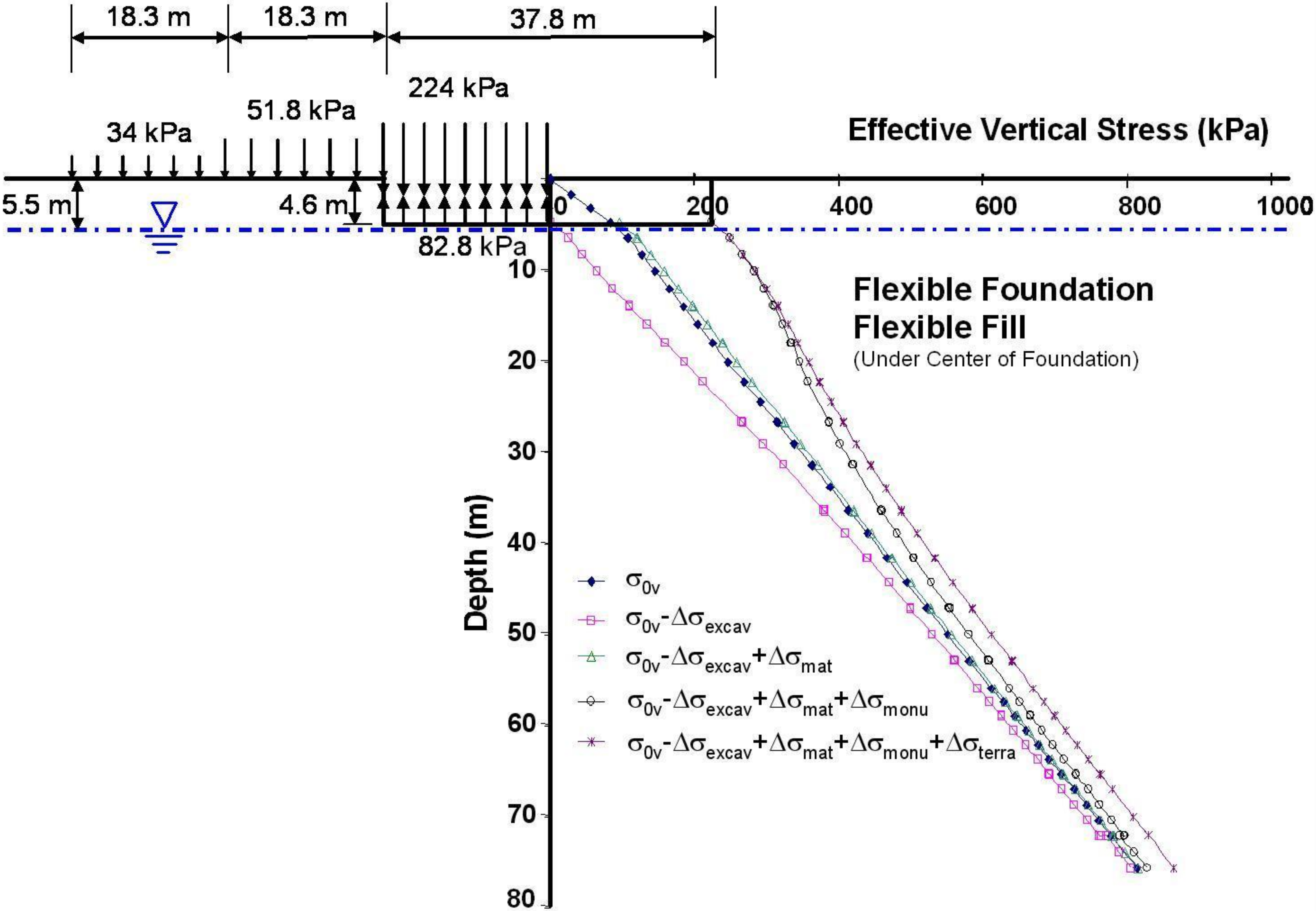
- Therefore $k = I\ E/B$
- k depends on the soil parameter and the size of the foundation
- If $k = 20000\ kN/m^3$ for a 1 m footing
- Then $k = 2000\ kN/m^3$ for a 10 m footing

Modulus of Subgrade Reaction

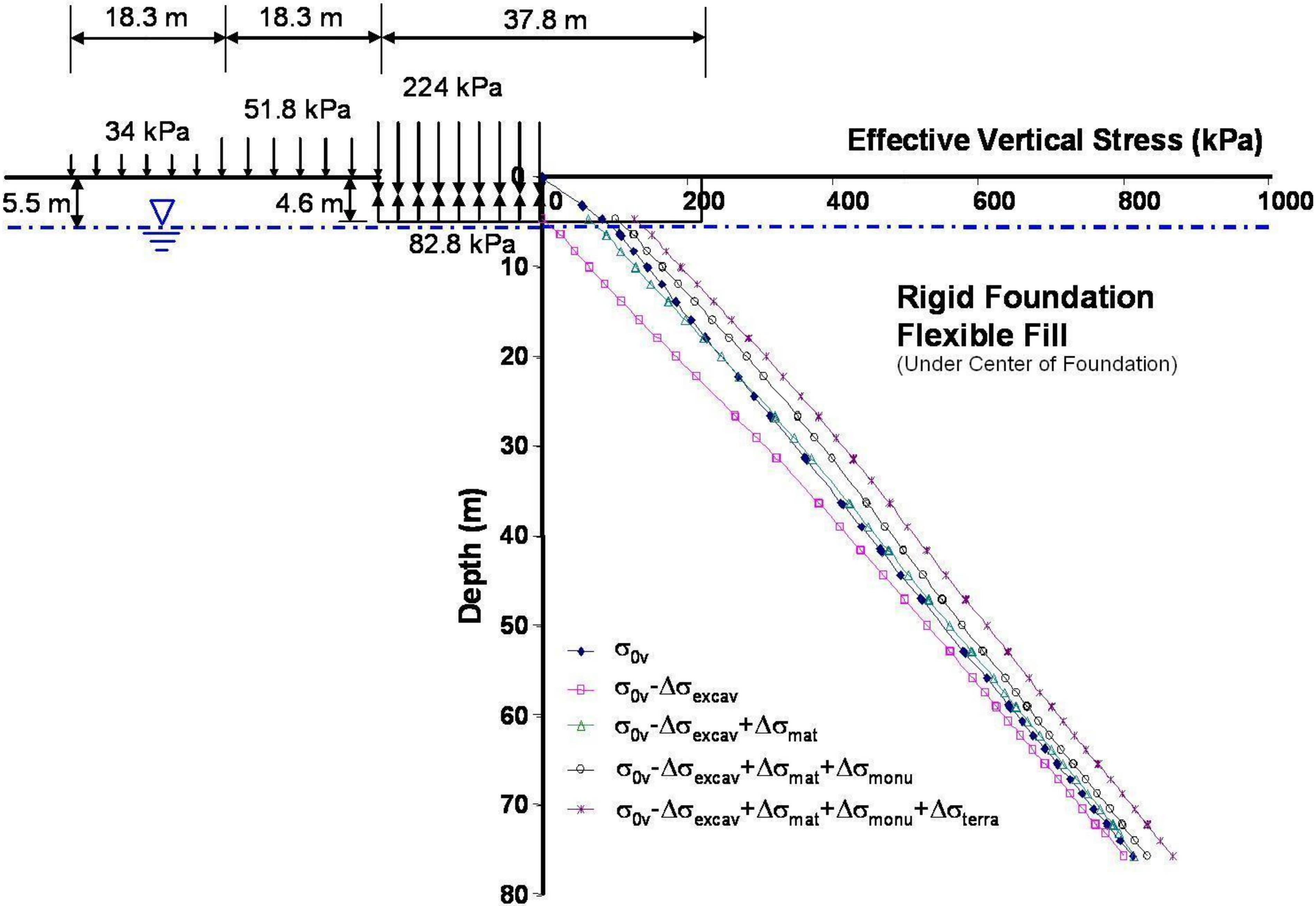
- **s = p/k** **s = IpB/E**
- A 1x1 m footing loaded with 100 kN settles 10 mm. Pressure is 100 kN/m^2
- A 10x10 m footing loaded with 10000 kN settles 10 mm according to subgrade modulus. Pressure is 100 kN/m^2
- A 10x10 m footing loaded with 10000 kN settles 100 mm according to elasticity.

Stress Distributions





18.3 m
18.3 m
37.8 m
224 kPa
51.8 kPa
34 kPa
Effective Vertical Stress (kPa)
5.5 m
4.6 m
82.8 kPa
0
200
400
600
800
1000
10
20
30
40
50
60
70
80
Depth (m)
Flexible Foundation
Flexible Fill
(Under Center of Foundation)
σ_{0v}
$\sigma_{0v}-\Delta\sigma_{excav}$
$\sigma_{0v}-\Delta\sigma_{excav}+\Delta\sigma_{mat}$
$\sigma_{0v}-\Delta\sigma_{excav}+\Delta\sigma_{mat}+\Delta\sigma_{monu}$
$\sigma_{0v}-\Delta\sigma_{excav}+\Delta\sigma_{mat}+\Delta\sigma_{monu}+\Delta\sigma_{terra}$



18.3 m
18.3 m
37.8 m
224 kPa
51.8 kPa
34 kPa
Effective Vertical Stress (kPa)
0
200
400
600
800
1000
5.5 m
4.6 m
82.8 kPa
Rigid Foundation
Flexible Fill
(Under Center of Foundation)
Depth (m)
0
10
20
30
40
50
60
70
80
σ_{0v}
$\sigma_{0v}-\Delta\sigma_{excav}$
$\sigma_{0v}-\Delta\sigma_{excav}+\Delta\sigma_{mat}$
$\sigma_{0v}-\Delta\sigma_{excav}+\Delta\sigma_{mat}+\Delta\sigma_{monu}$
$\sigma_{0v}-\Delta\sigma_{excav}+\Delta\sigma_{mat}+\Delta\sigma_{monu}+\Delta\sigma_{terra}$

Depth of Influence

- Two definitions for the depth of influence:
  - Depth at which the pressure has decreased to 10% of the applied surface pressure
  - Depth at which the settlement is 10% of the settlement at the surface
- The zone of influence depends on which definition is used and on the modulus profile of the soil

Settlement – consolidation test

Case 7

- Assumptions:
  - Water at base of foundation
  - Added Fill
  - No rebound

Case 8

- Assumptions:
  - Water at base of foundation
  - Added Fill
  - Rebound of excavation

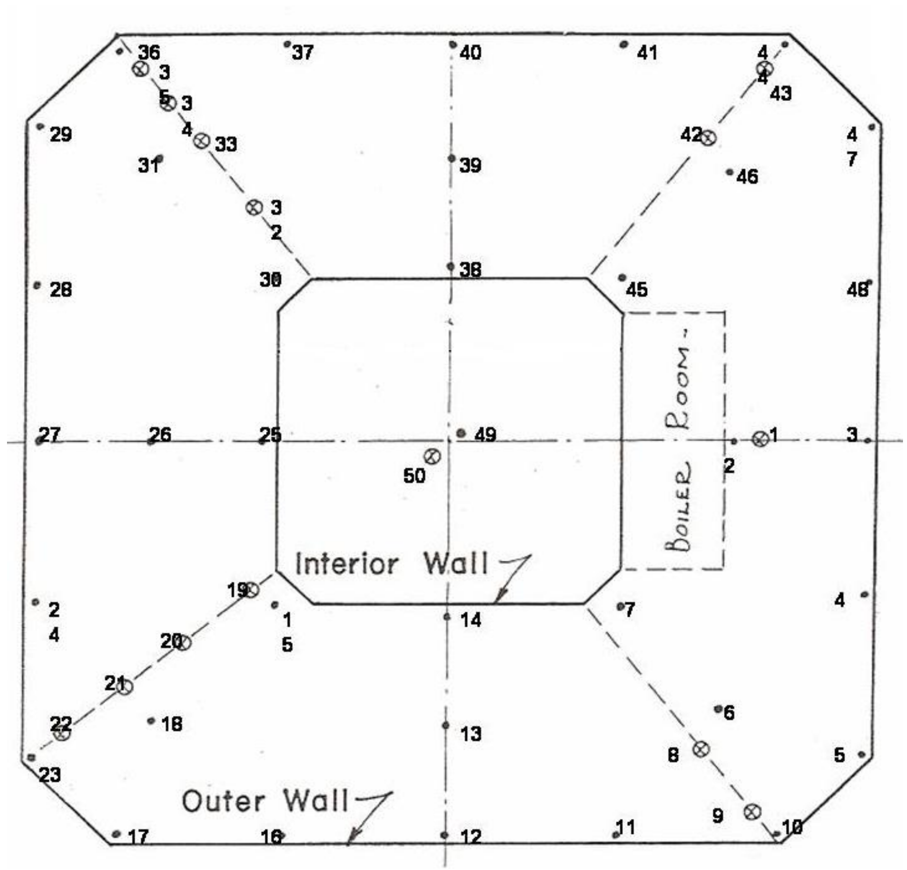
Case	Subcase	2007 Tests (m)	1953 Tests (m)
7	A	0.353	0.392
	CUNLOAD	0.561	0.481
	CLOAD	0.448	0.359
8	A	0.454	0.602
	CUNLOAD	1.002	0.854
	CLOAD	0.781	0.587

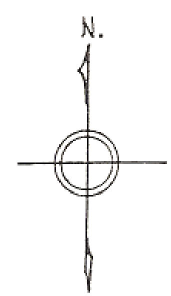
SETTLEMENT

Consolidation Tests		CPT(Schmertmann)		PMT(First modulus)		Measured in 2006
1953 (long term)	2007 (long term)	Short term	Long term	Short term	Long term	
0.392 m	0.353 m	0.19 m	0.299 m	0.145 m	0.291 m	0.328 m

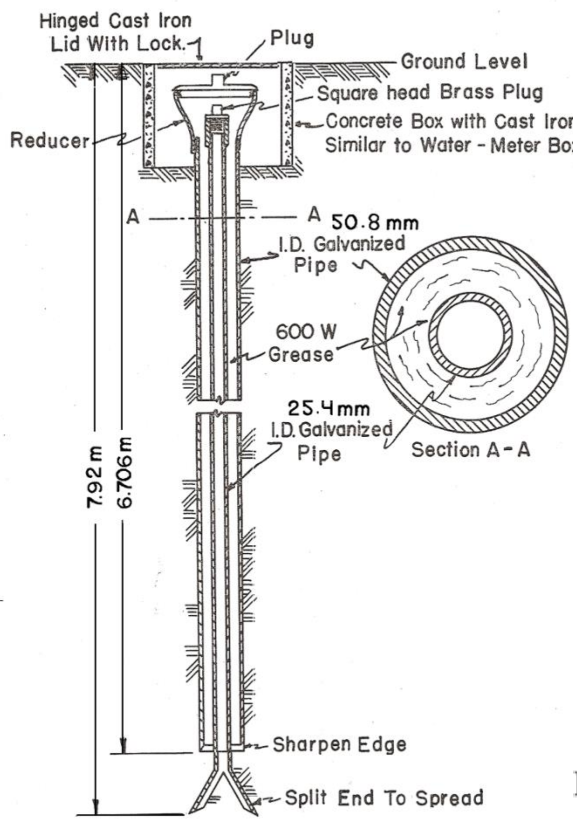
Reference Points

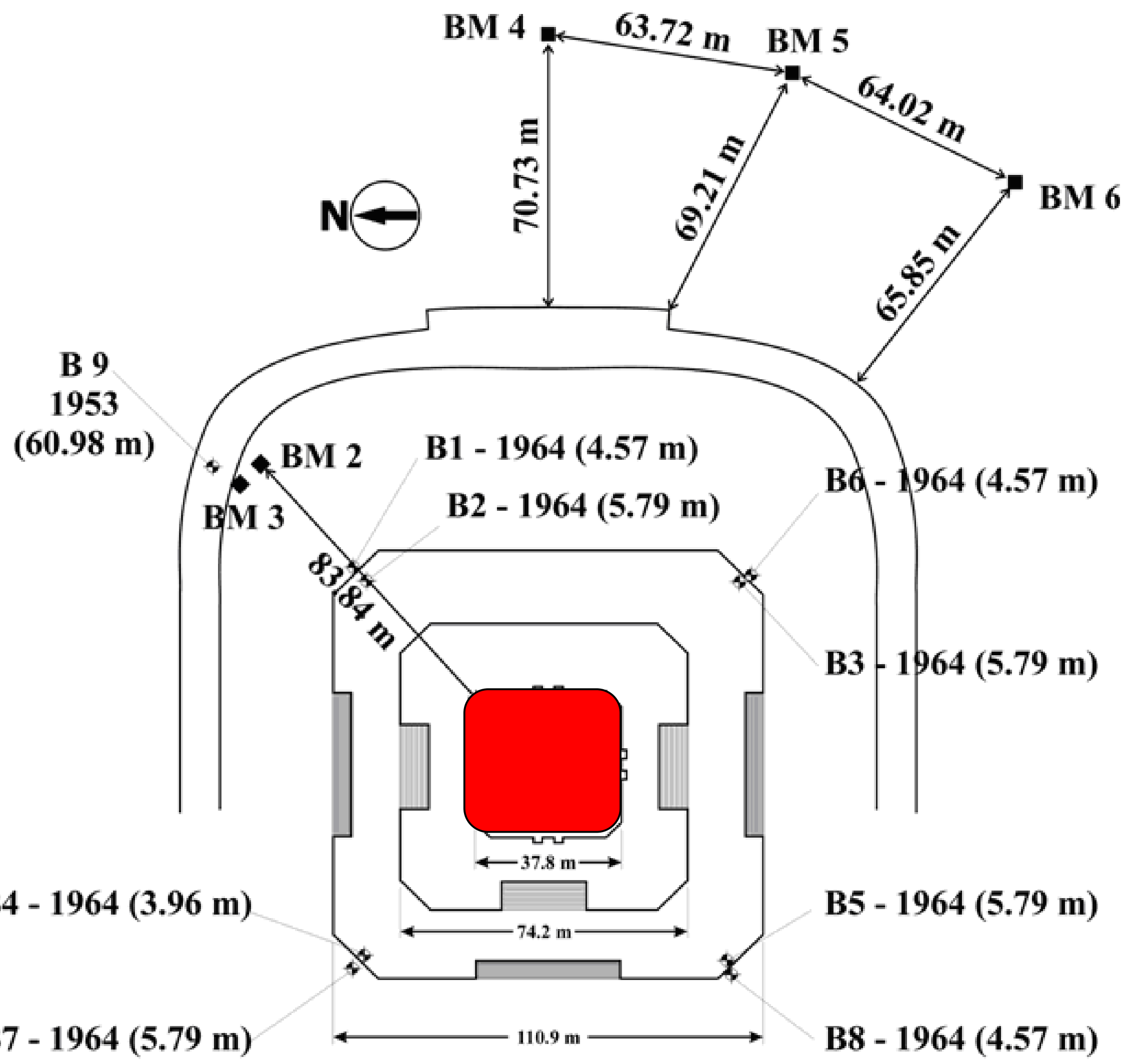
- Dawson established 50 reference points around the foundation





Benchmarks-6.7 m deep

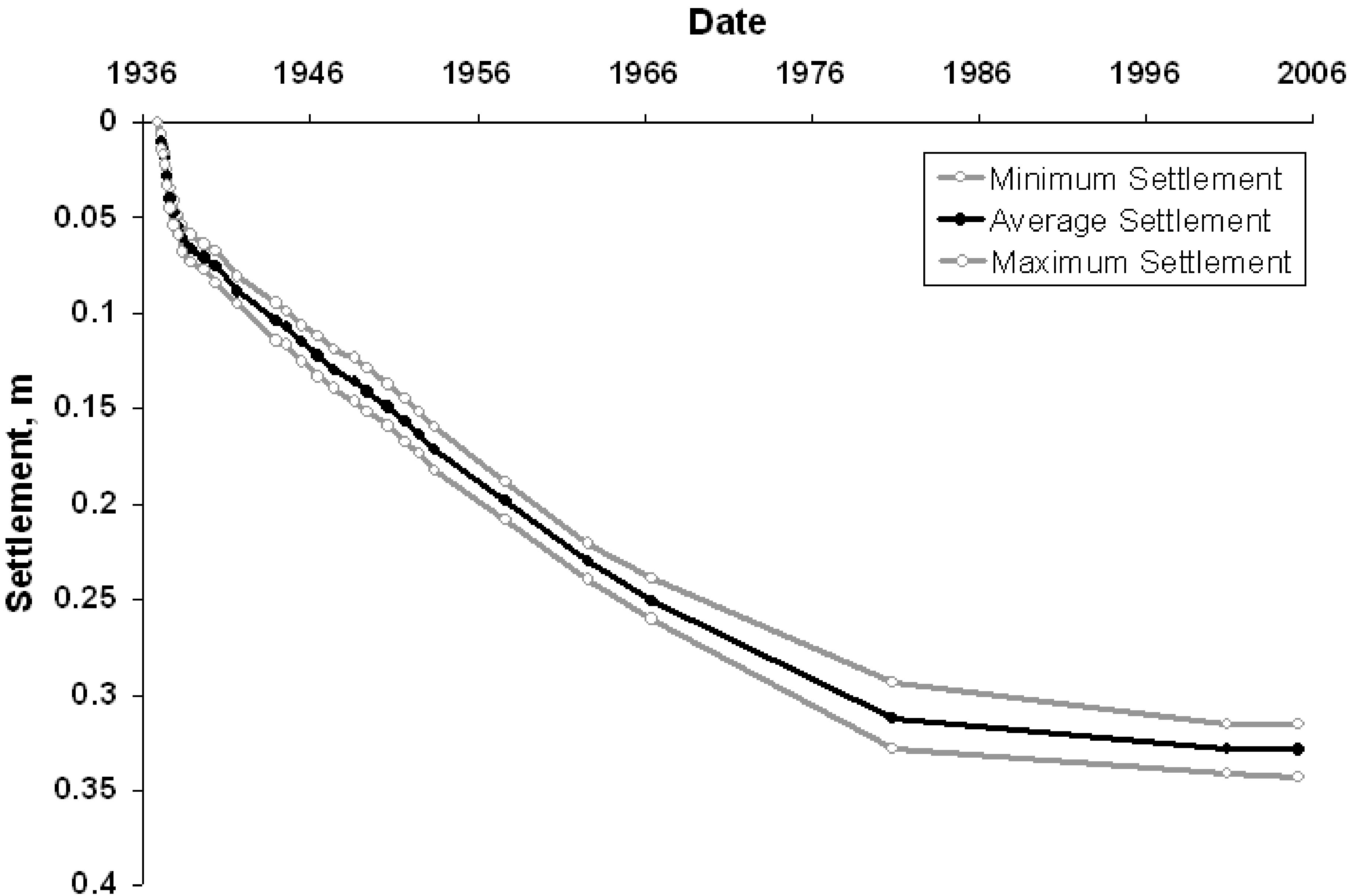




Actual Settlement

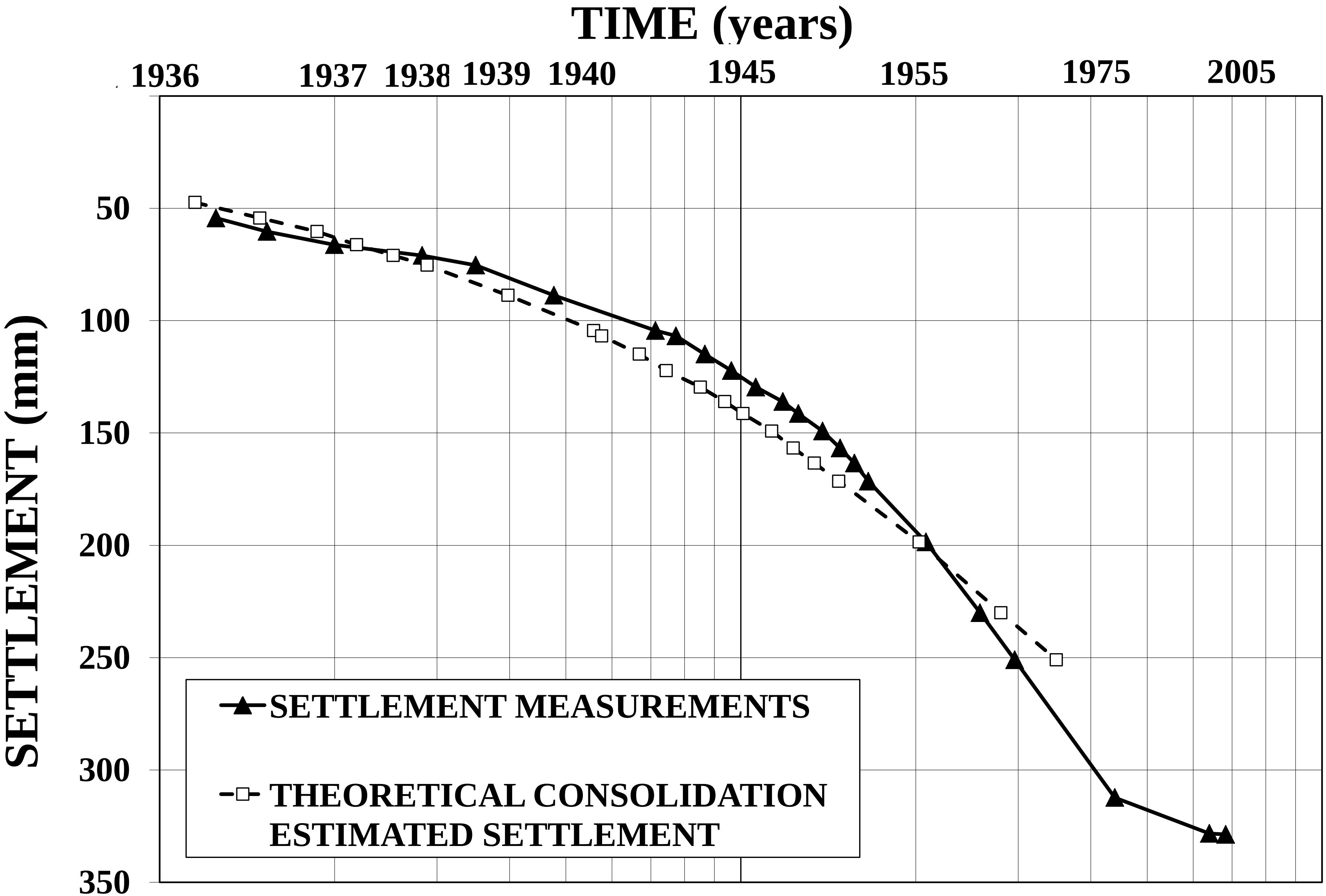
- Dawson established the elevations of the benchmarks and reference points on November 9, 1936 – two weeks after the foundation was poured
- Net soil pressure = 10.4 kPa
- Dawson took 26 settlement readings between 1937 and 1966

Actual Settlement

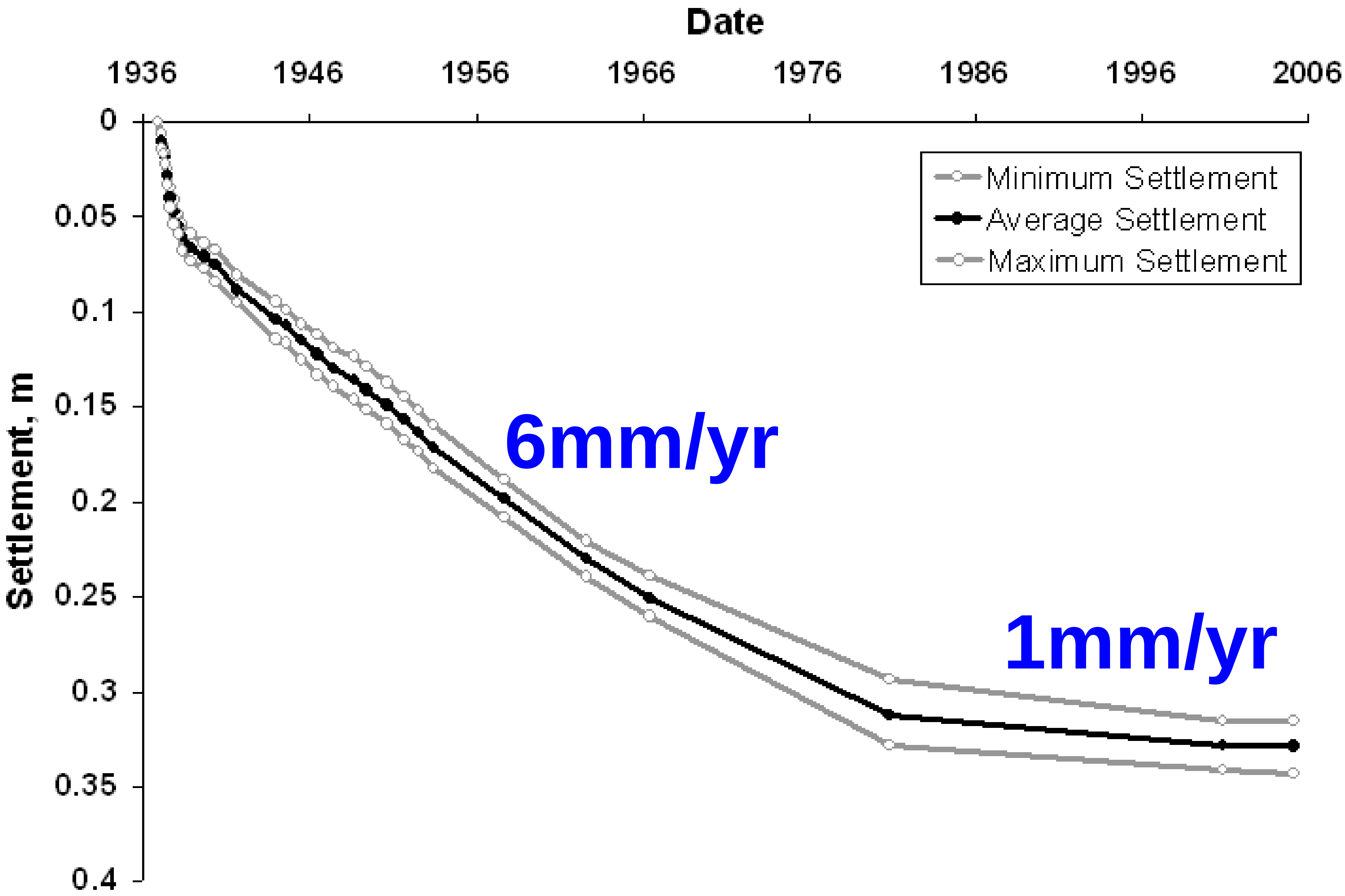


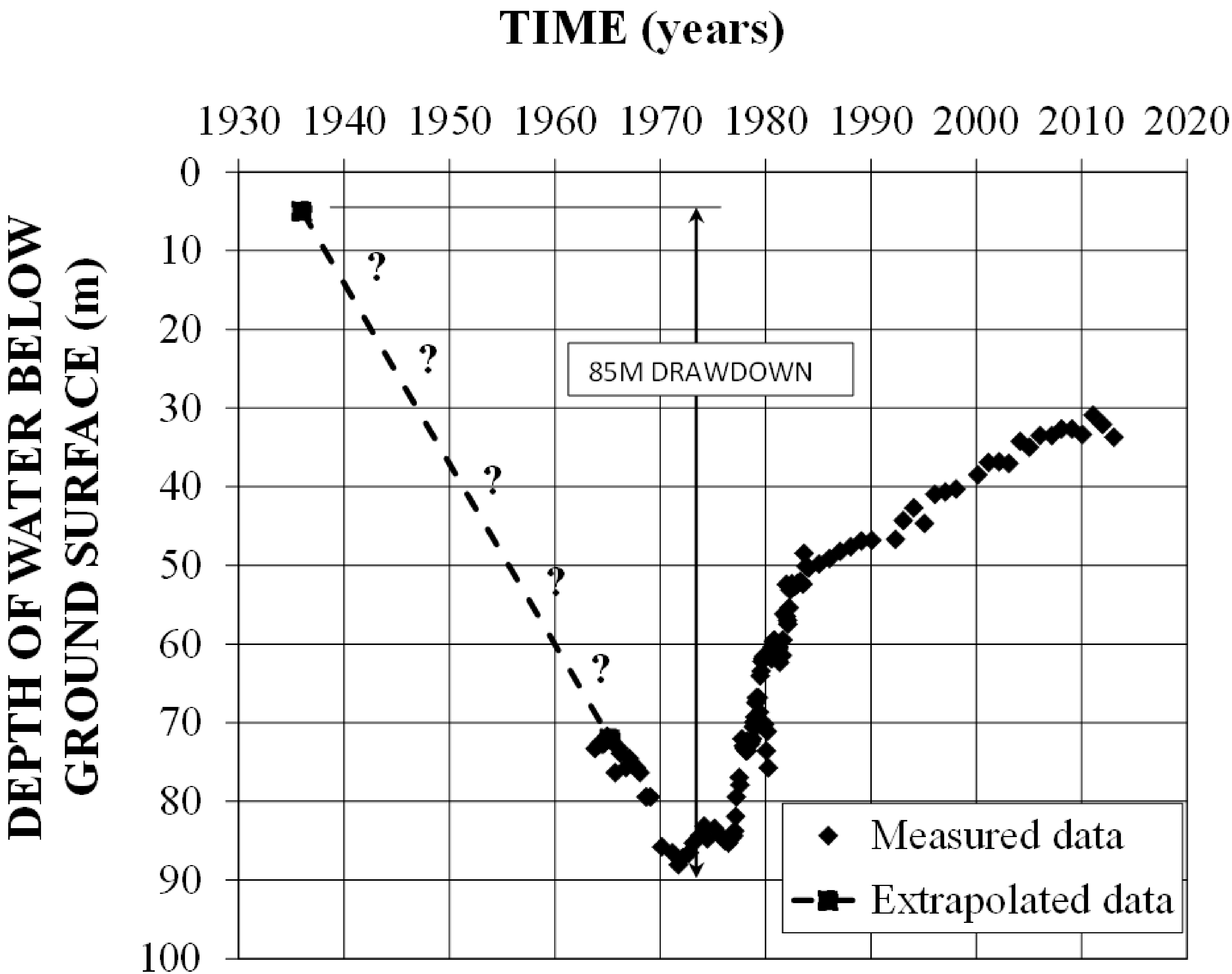
Subsidence

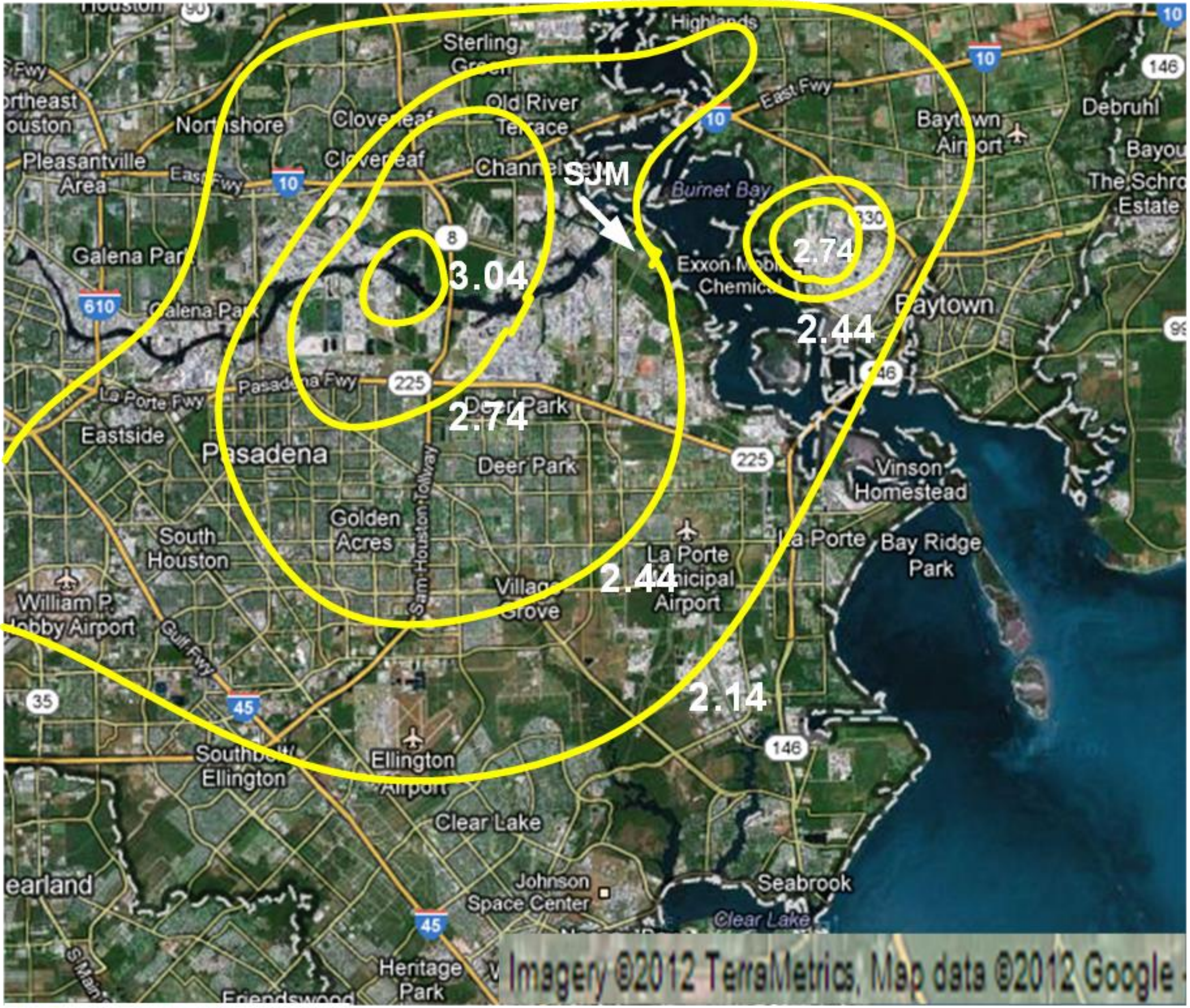
- The areas that have the greatest groundwater extraction have subsided about 3 m.
- The rate of subsidence in the Houston area ranged from 31 to 76 millimeters per year.
- Assuming uniform subsidence around the San Jacinto Monument, the benchmarks and reference points would not see differential settlement.



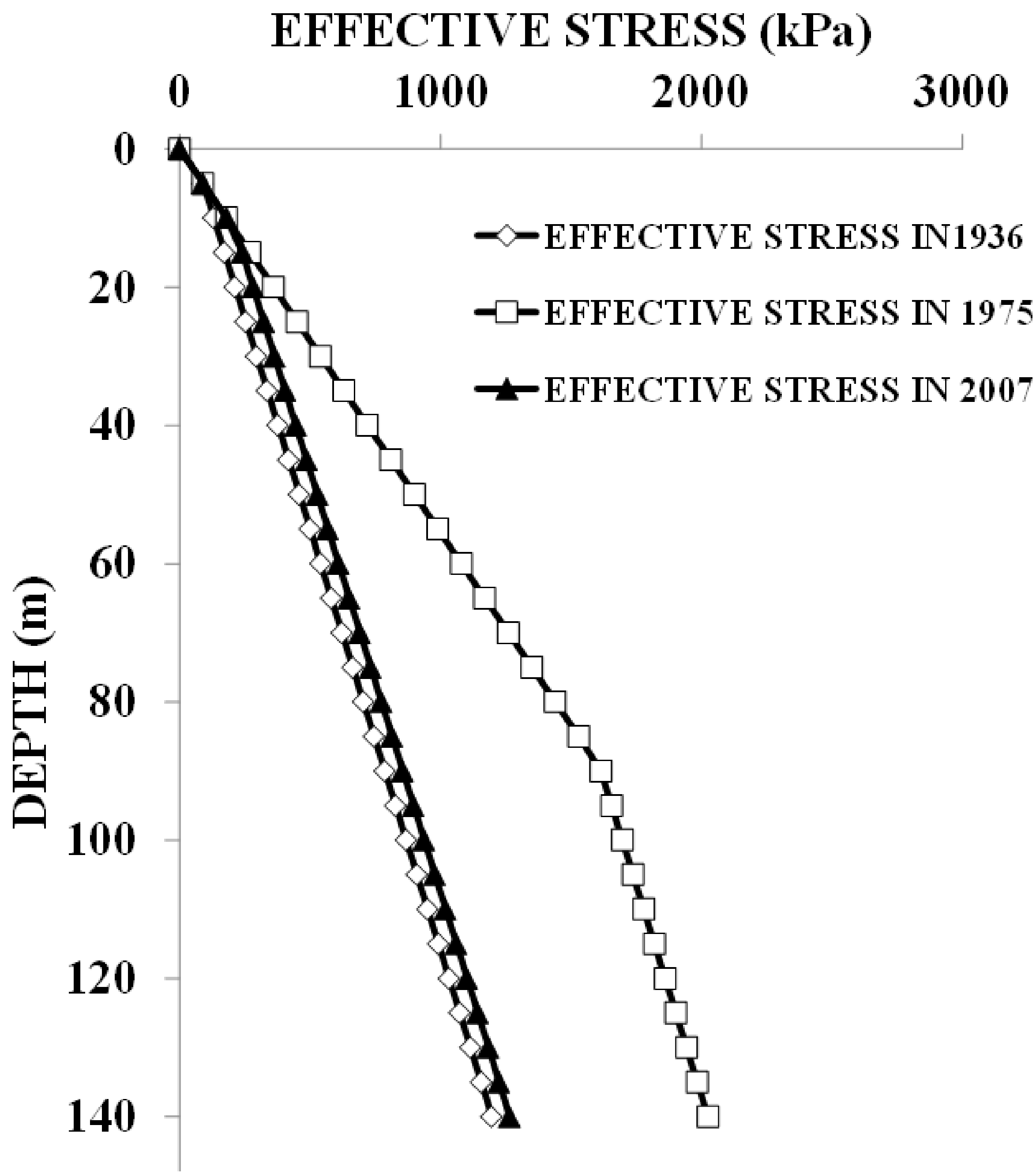
Jean-Louis Briaud – Texas A&M University


Date
1936
1946
1956
1966
1976
1986
1996
2006
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Settlement, m
Minimum Settlement
Average Settlement
Maximum Settlement
6mm/yr
1mm/yr


TIME (years)
1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
DEPTH OF WATER BELOW GROUND SURFACE (m)
0 10 20 30 40 50 60 70 80 90 100
85M DRAWDOWN
?
?
?
?
?
Measured data
Extrapolated data

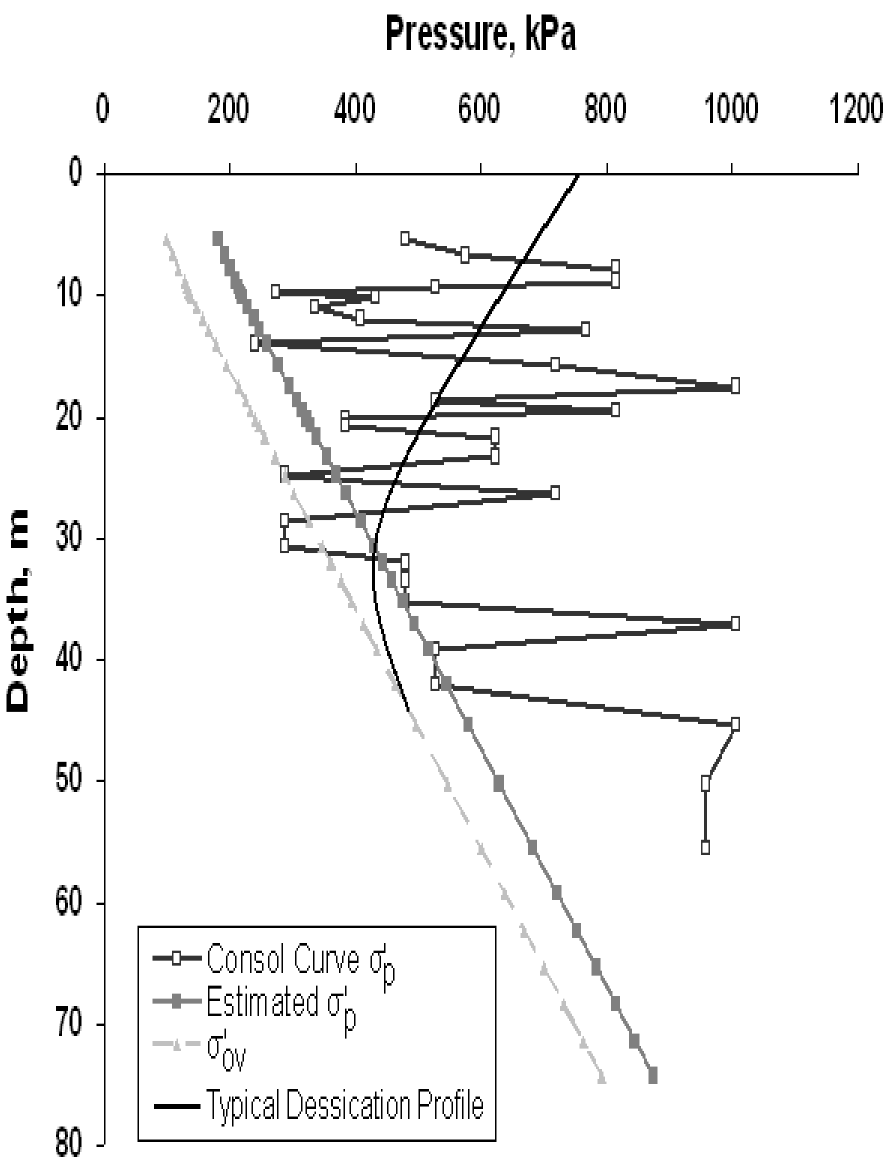


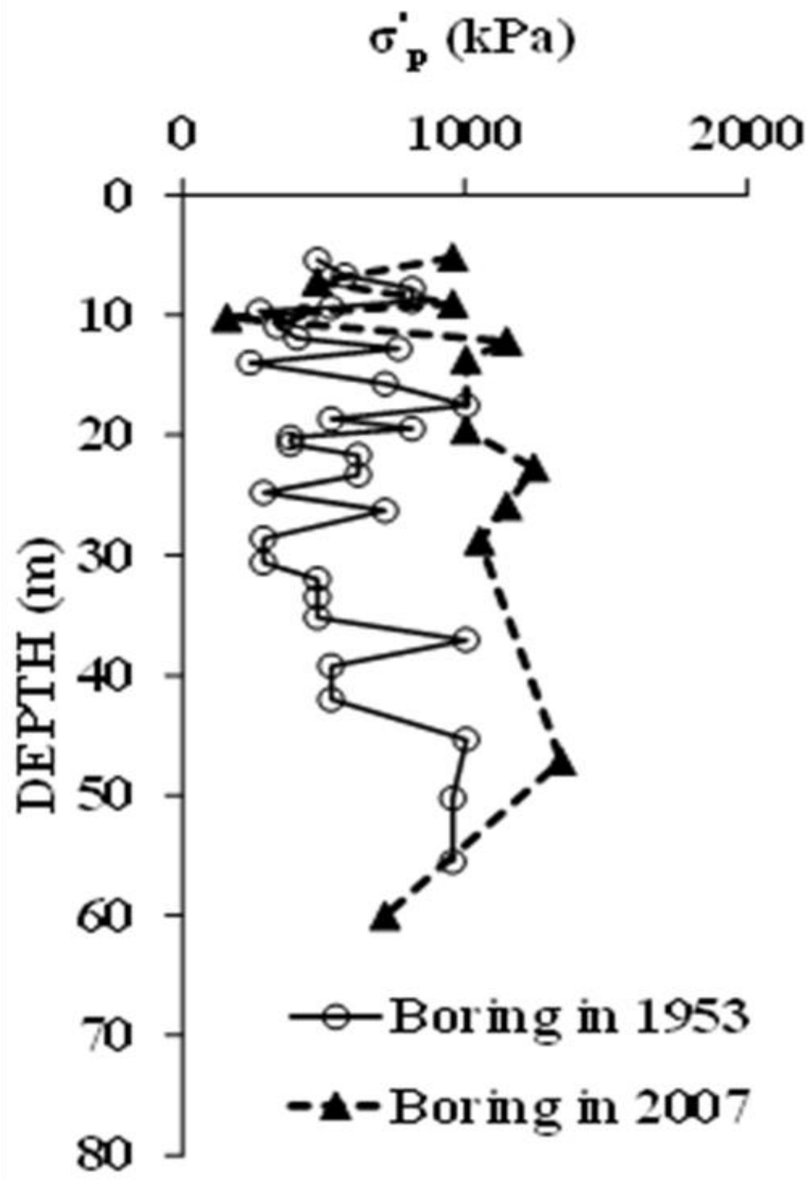
Picture obtained from Google earth

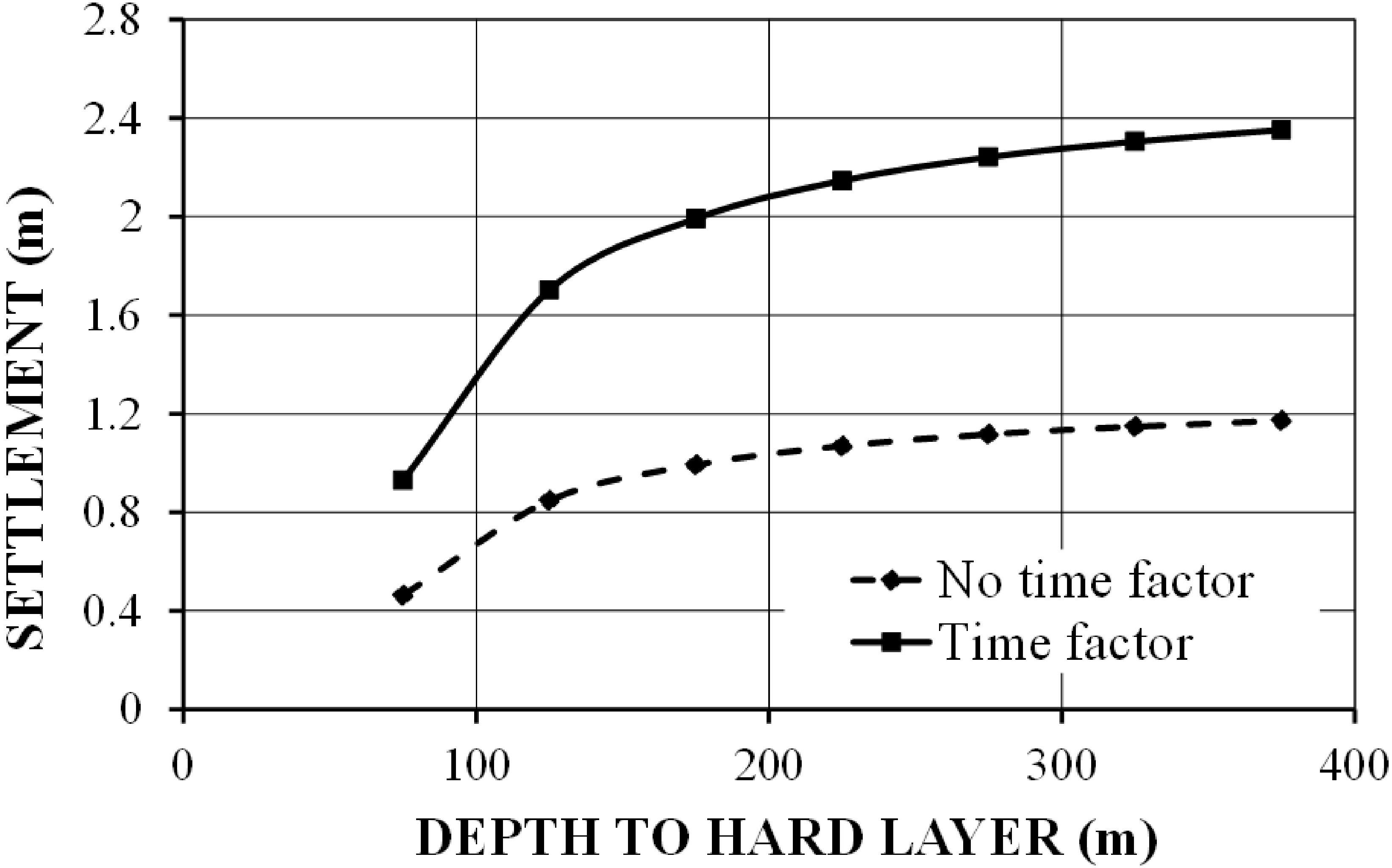


EFFECTIVE STRESS (kPa)
0
1000
2000
3000
0
20
40
60
80
100
120
140
DEPTH (m)
EFFECTIVE STRESS IN1936
EFFECTIVE STRESS IN 1975
EFFECTIVE STRESS IN 2007

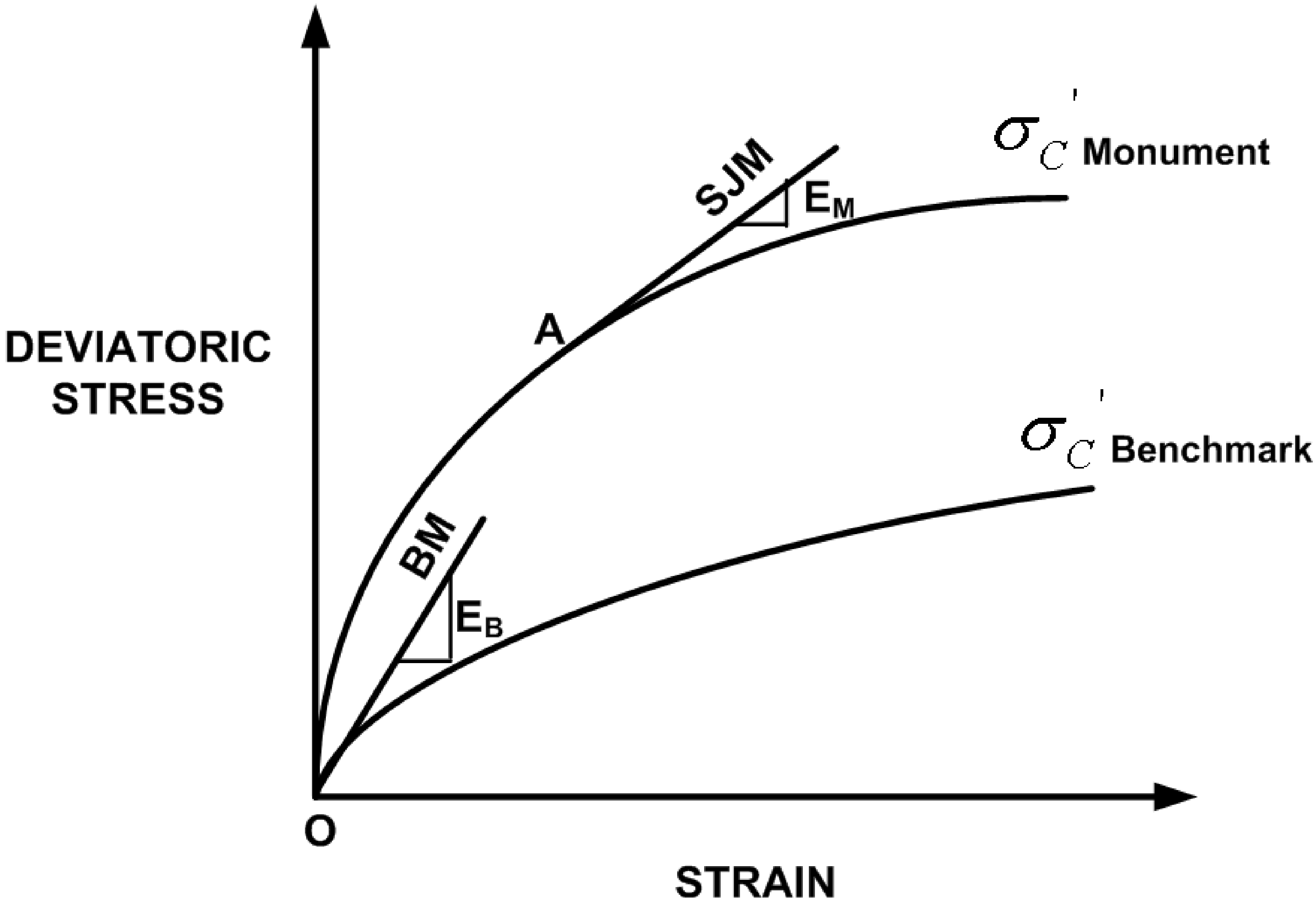
Stress History







SETTLEMENT (m)
2.8
2.4
2
1.6
1.2
0.8
0.4
0
0
100
200
300
400
DEPTH TO HARD LAYER (m)
No time factor
Time factor


DEVIATORIC STRESS
STRAIN
O
A
SJM
E_M
BM
E_B
σ_C' Monument
σ_C' Benchmark

SETTLEMENT

Scenario	Benchmark Settlement	Monument Settlement	Differential Settlement
Monument only, no subsidence	0.019 m	0.288 m	0.269 m
Subsidence in the free field, no Monument	2.613 m	2.613 m	0 m
Monument plus subsidence	2.617 m	2.919 m	0.302 m

SETTLEMENT

Measured (mm)	CPT (mm)	PMT (mm)	Consolidation (mm)
After accounting for subsidence – 295	Short term - 190 Long term - 299	Short term -145 Long term – 291	 Long term - 353

Conclusions

- *Stress increase with depth*:
  - For rigid mats, use flexible stress increase solutions. The soil redistributes the pressure in the long term.
  - Go to a depth of 2B
  - Divide that depth in about 10 layers
  - Calculate the decrease in stress due to excavation in each layer
  - Calculate the increase in stress due to the mat in each layer
  - Calculate the increase in stress due to the structure in each layer

Conclusions

- *Consolidation Testing*:
  - Think about what the soil will go through in the field.
  - Upon extrusion from the Shelby tube the sample is unloaded. Consolidation tests start as reloading tests
  - Apply loading up to the initial vertical stress, σ'_{ov}, for the sample
  - Unload the sample by an amount equal to the pressure removed due to excavation
  - Reload the sample in steps up to at least $\sigma'_{ov} + \Delta\sigma_{load}$

Conclusions

- *Settlement calculations*:
  - Perform calculations for the center of each layer
  - Use the void ratios from the consolidation curves $s = H\ \Delta e/(1+e_o)$
  - Calculate separately the rebound during excavation, the settlement of the mat, the settlement of the structure.
  - Remember that heterogeneity is scale dependent.

Conclusions

- *Settlement calculations*:
  - For long term settlement, E/s_u = 123
  - If available, use a 3-D numerical method to determine settlement. In this fashion, the stress increase and the stiffness profile are automatically taken care of.
  - Which settlement is important? After the mat is poured, after a few floors, after completion of the structure? Should the recompression settlement be included?


THANK YOU
http://ceprofs.civil.tamu.edu/briaud/