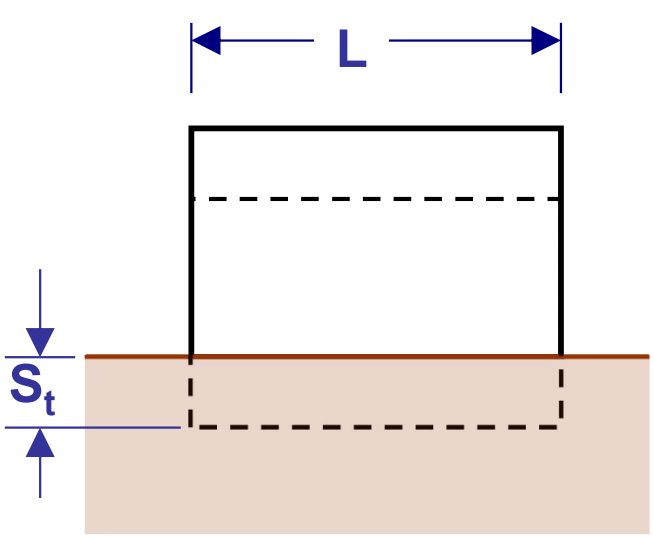
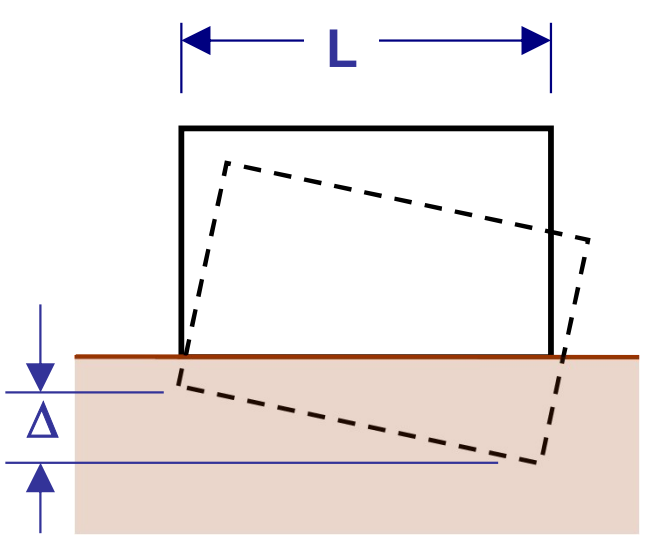
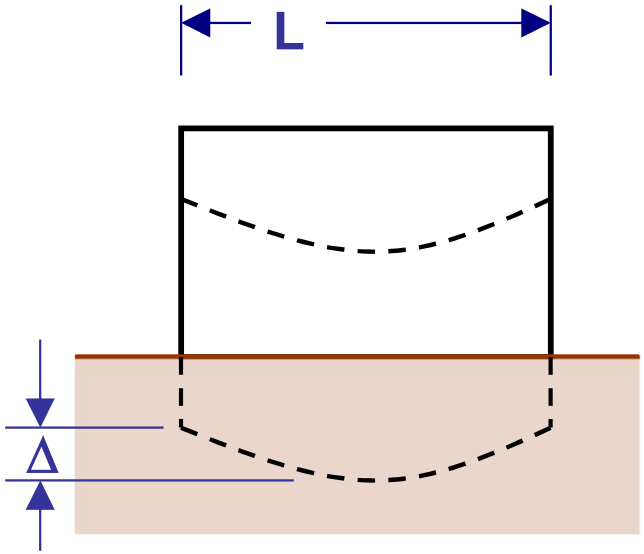
TYPES OF SETTLEMENT



Uniform Settlement



Tilt



Non-Uniform Settlement

Where:

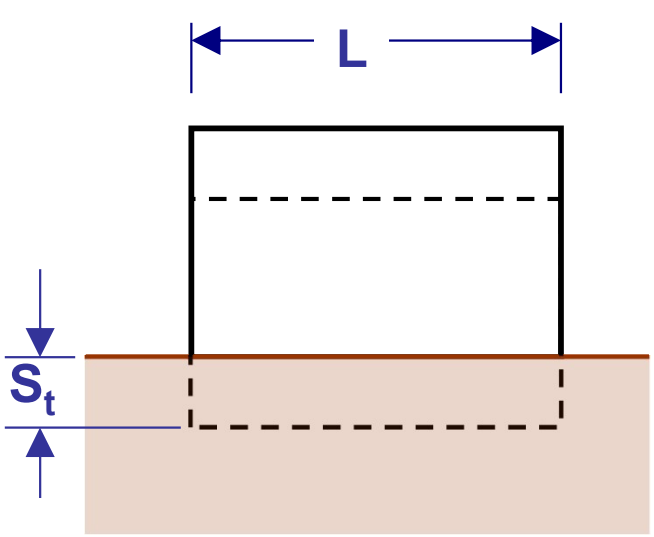
S_t = Total Settlement
(Typically limited to 1 inch)
Δ = Maximum Differential Settlement
L = Building (or Span) Length
Deflection Ratio = Δ/L

Table 2-1. Maximum Allowable S_t (EM 1110-1-1904)

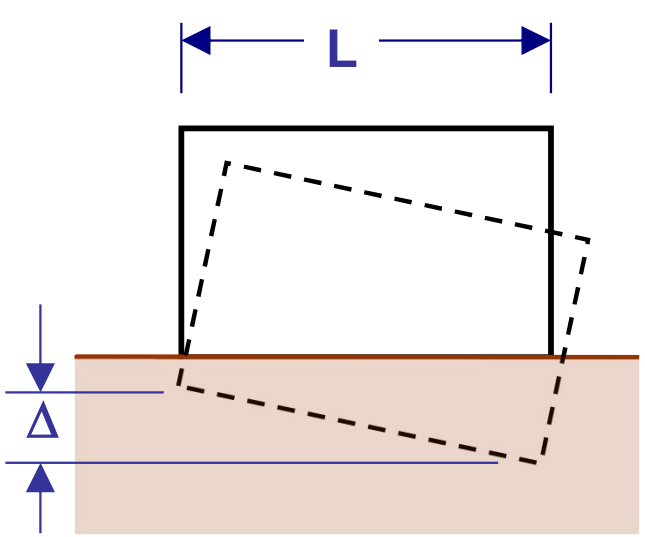
Type of Structure	Settlement, inches
Plain brick walls	
Length/Height ≥ 2.5	3
Length/Height ≤ 1.5	4
Framed structure	4
Reinforced brick walls and brick walls with reinforced concrete	6
Solid reinforced concrete foundations supporting smokestacks, silos, towers, etc	12

Figures after Crawford, 1972 (CBD-148)

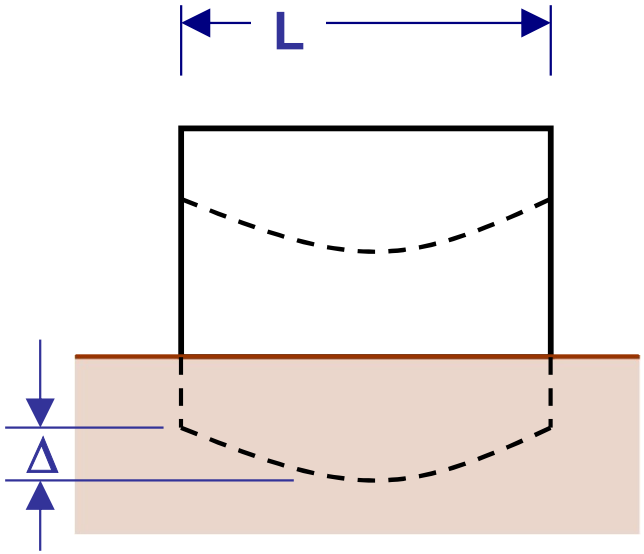
TYPES OF SETTLEMENT



Uniform Settlement



Tilt



Non-Uniform Settlement

Where:

S_t = Total Settlement
Δ = Maximum Differential Settlement
L = Building (or Span) Length
Deflection Ratio = Δ/L

Table 2-2. Limiting Δ/L (EM1110-1-1904)

Structure	Deflection Ratio, Δ/L: Sand and Hard Clay	Deflection Ratio, Δ/L: Plastic Clay
Buildings with plain brick walls		
Length/Height ≥ 3	1/3333	1/2500
Length/Height ≥ 5	1/2000	1/1500
One story mills; between columns for brick clad column frames	1/1000	1/1000
Steel and concrete frame	1/500	1/500

Figures after Crawford, 1972 (CBD-148)

DIFFERENTIAL SETTLEMENT

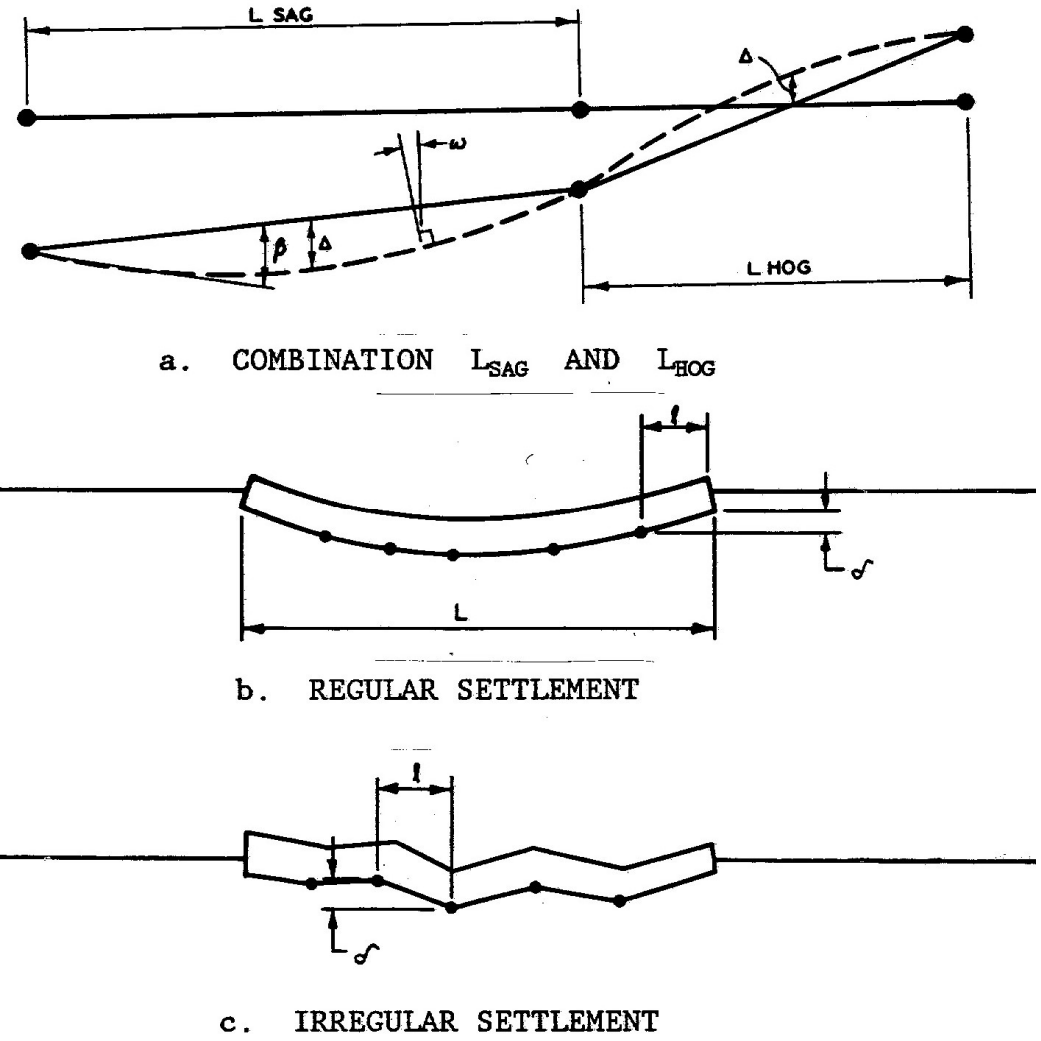


Figure 2-1. EM1110-1-1904

Where:

Δ = Max. Differential Settlement
δ = Differential Settlement between 2 Pts
L = Building (or Span) Length
ℓ = Length between 2 Points
Angular Distortion $\beta = \delta/\ell$

Differential Settlement

Interference w/ Adjacent Structures
Disruption of Machinery & People
Cracking
Jammed Floors & Windows
Uneven Floors
Reduction of waterstop efficiency
Structural Failure

DIFFERENTIAL SETTLEMENT

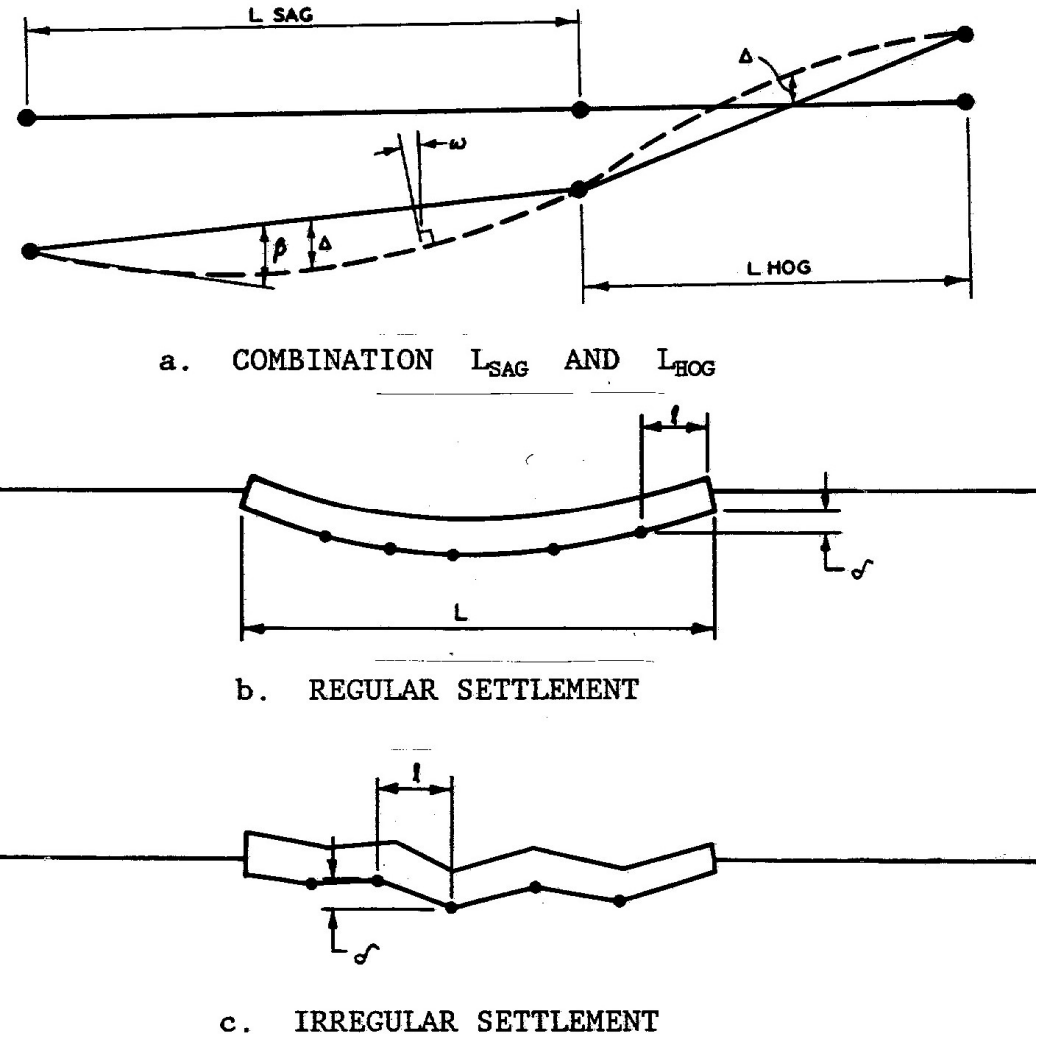


Figure 2-1. EM1110-1-1904

Table 2-3. Limiting β/l to Avoid Damage (EM1110-1-1904)

Situation	Length Height	Allowable Angular Distortion, $\beta = \delta/\ell$
Hogging of unreinforced load-bearing walls		1/2000
Load bearing brick, tile, or concrete block walls	≥ 5 ≤ 3	1/1250 1/2500
Sagging of unreinforced load-bearing walls		1/1000
Machinery sensitive to settlement		1/750
Frames with diagonals		1/600
No cracking in buildings; tilt of bridge abutments; tall slender structures such as stacks, silos, and water tanks on a rigid mat		1/500
Steel or reinforced concrete frame with brick, block, plaster or stucco finish	≥ 5 ≤ 3	1/500 1/1000
Circular steel tanks on flexible base with floating top; steel or reinforced concrete frames with insensitive finish such as dry wall, glass, panels		1/300 - 1/500
Cracking in panel walls; problems with overhead cranes		1/300
Tilting of high rigid buildings		1/250
Structural damage in buildings; flexible brick walls with length/height ratio > 4		1/150
Circular steel tanks on flexible base with fixed top; steel framing with flexible siding		1/125

*Based on field surveys of damage

DIFFERENTIAL SETTLEMENT

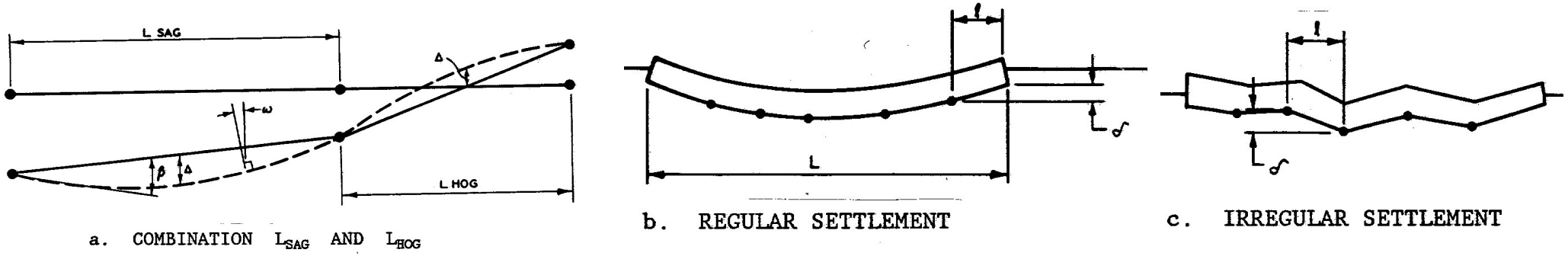


Figure 2-1. EM1110-1-1904

Table 2-3. Empirical Correlations between Δ and β (EM1110-1-1904)

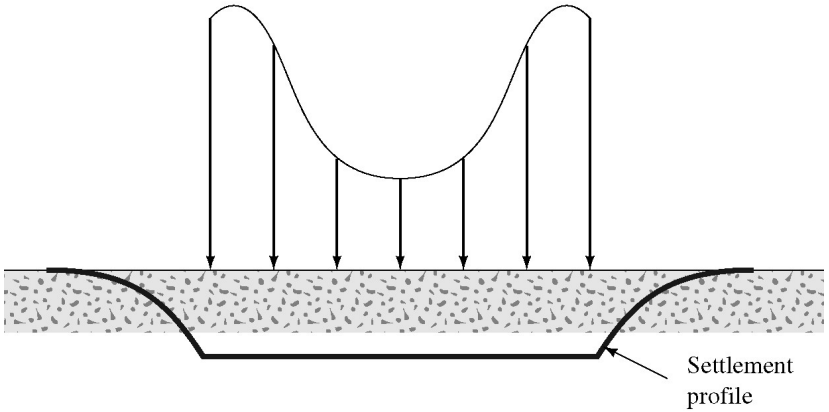
Soil	Foundation	Approximate β for Δ = 1 inch*
Sand	Mats	1/750
	Spread footings	1/600
Varved silt	Rectangular mats	1/1000 to 1/2000
	Square mats	1/2000 to 1/3000
	Spread footings	1/600
Clay	Mats	1/1250
	Spread footings	1/1000

* β increases roughly in proportion with Δ. For Δ = 2 inches, β is about twice as large as those shown; for Δ = 3 inches, three times as large, etc.

FOUNDATION CONTACT PRESSURES

RIGID FOUNDATIONS

Typically Experience
Uniform Settlement



FLEXIBLE FOUNDATIONS

Typically Experience
Differential Settlement

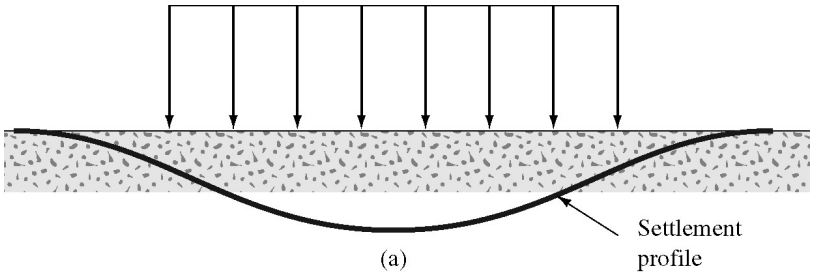


Figure 12-14. Das FGE (2005)

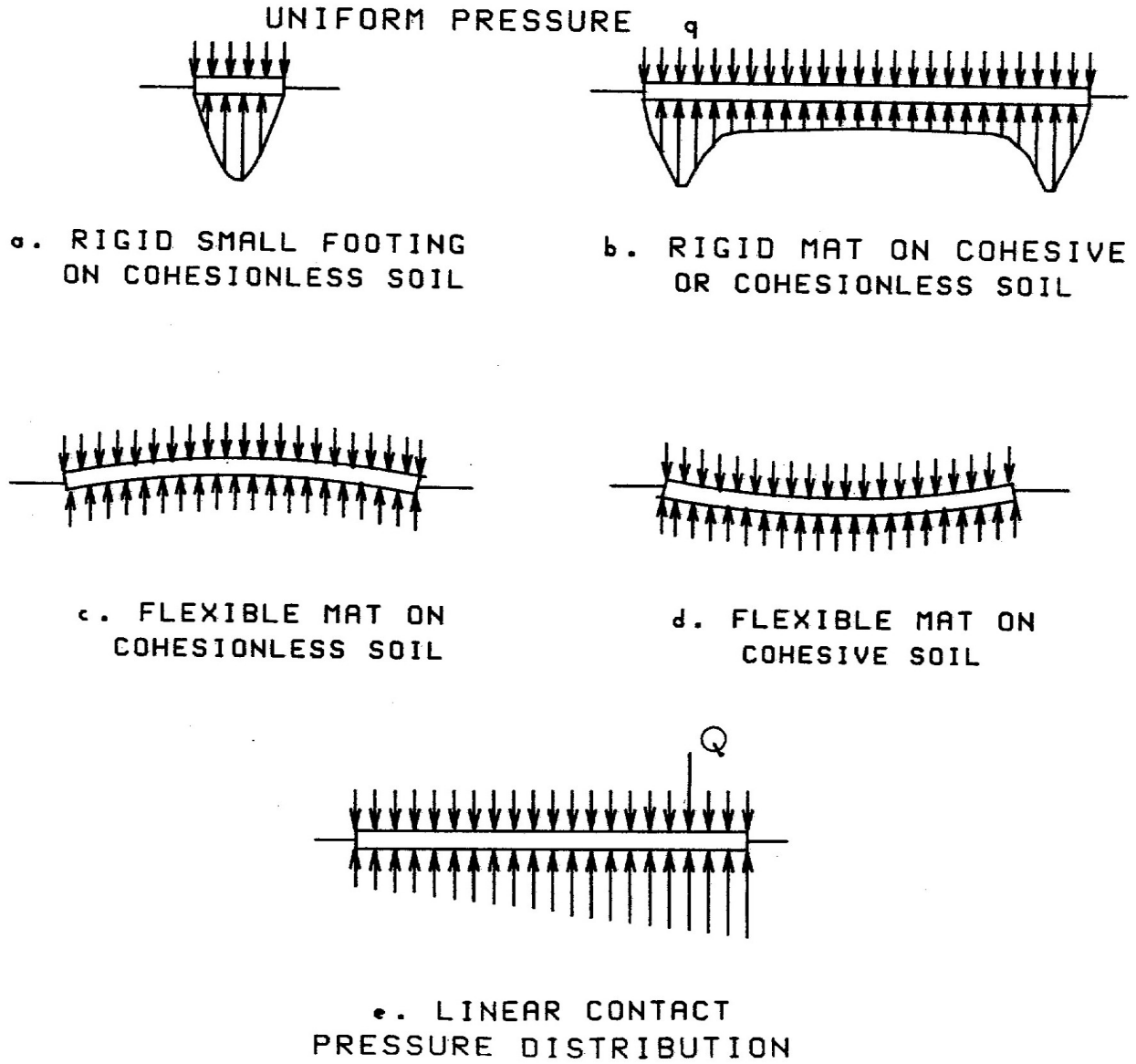


Figure 1-3. EM1110-1-1904

FOUNDATION SETTLEMENT COMPONENTS

Total Foundation Settlement = Elastic Settlement + Consolidation Settlement

a.k.a. Immediate.
Primary Settlement Component
of Sands but also occurs in
Cohesive Soils.

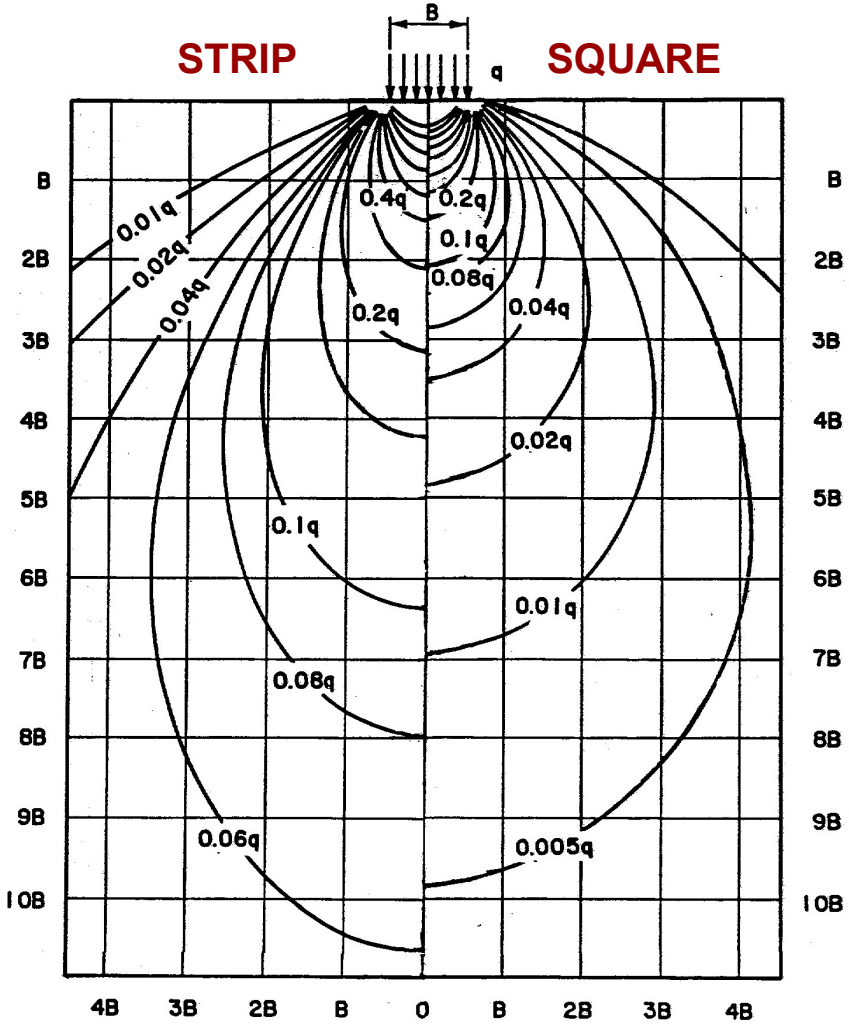
a.k.a. Long-Term.
Primary Settlement Component
of Cohesive Soils.
Covered in Soil Mechanics

$$S_t = S_e + S_c$$

WHAT DO YOU NEED TO CALCULATE SETTLEMENT?

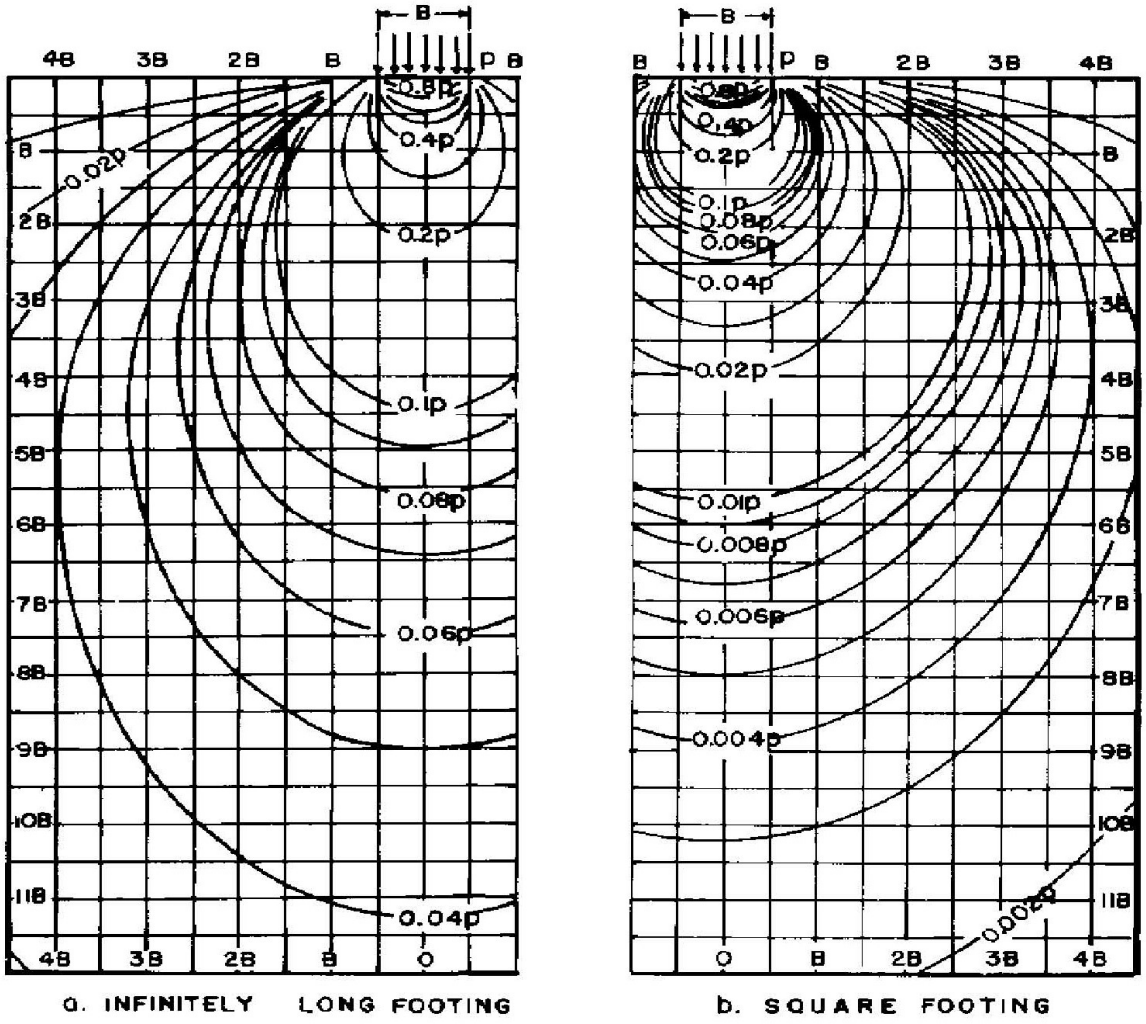
Foundation Loads/Pressures
Changes in Vertical Soil Stress ($\Delta\sigma$)
Foundation Size and Location
Soil Profile
Soil Properties:
Elastic Settlement: E_s, μ
Consolidation Settlement: 1D Consolidation Test Data

VERTICAL STRESS INCREASE ($\Delta\sigma$) IN SOILS (REVIEW)



Boussinesq Distributions

Figure 1-2. EM 1110-1-1904

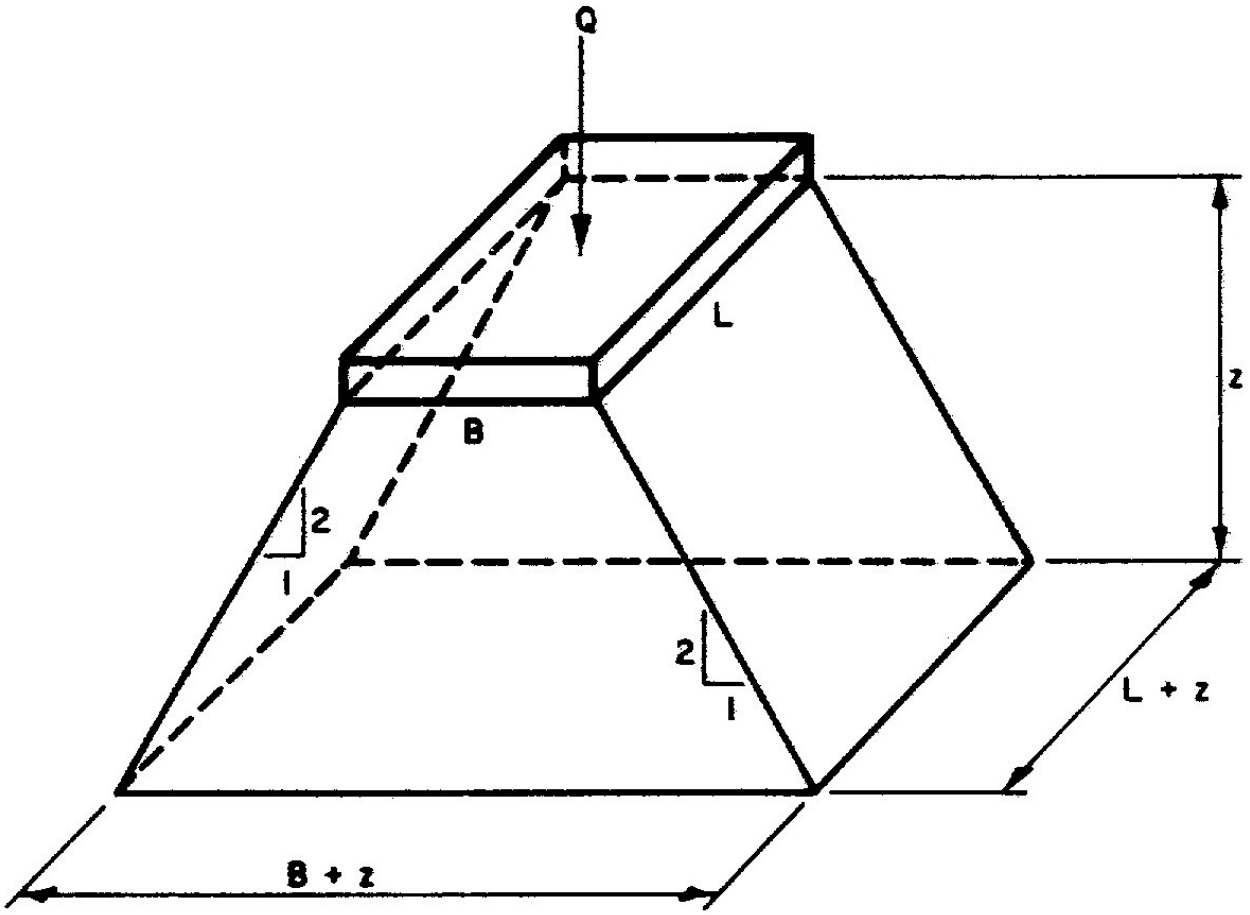


Westergaard Distributions

Figure 11. NAVFAC DM7.01

VERTICAL STRESS INCREASE ($\Delta\sigma$) IN SOILS (REVIEW)

APPROXIMATE 2V:1H DISTRIBUTION METHOD



$$\Delta\sigma = \frac{Q}{(B+z)(L+z)}$$

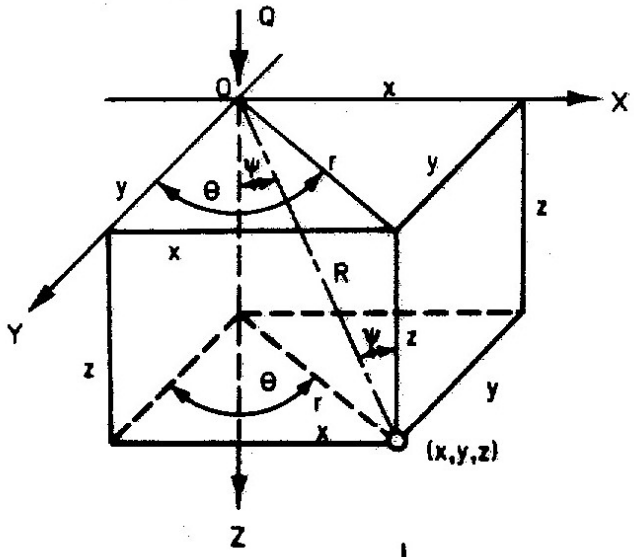
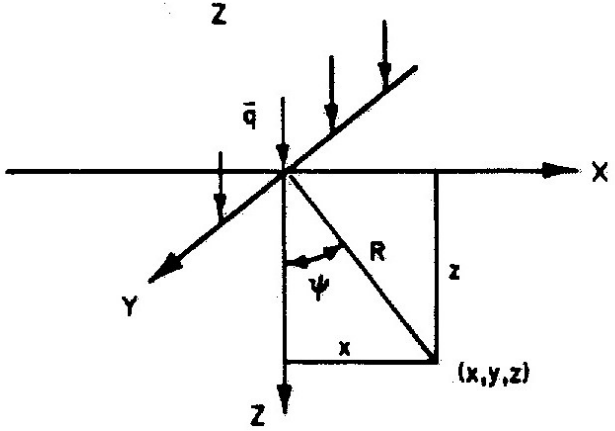
Where:

$\Delta\sigma$ = Change in Total Vertical Stress
Q = Applied Foundation Load
B = Foundation Width
L = Foundation Length

Figure C-1. EM1110-1-1904

VERTICAL STRESS INCREASE ($\Delta\sigma$) IN SOILS (REVIEW)

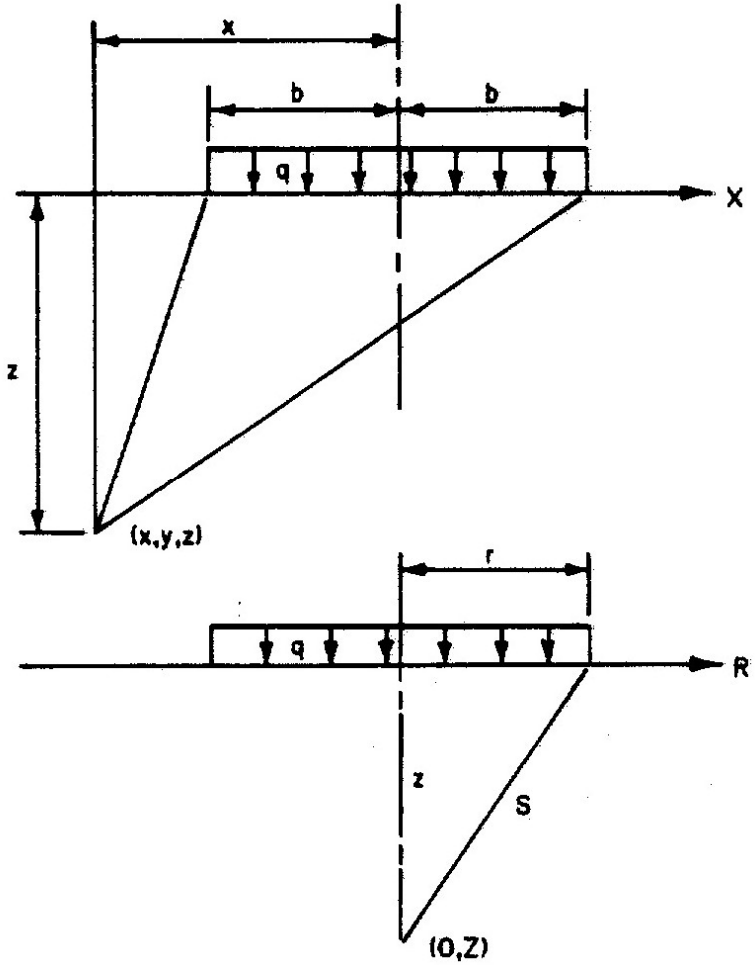
Table C-1. Boussinesq Solutions (EM 1110-1-1904).

TYPE OF LOAD NORMAL TO SURFACE	EQUATION FOR $\Delta\sigma_z$	COORDINATE SYSTEM
POINT	$\frac{3Q}{2\pi R^2}\cos^3\psi$ Q = NORMAL LOAD, TONS $r^2 = x^2 + y^2$ $R^2 = r^2 + z^2$	
LINE	$\frac{2\bar{q}z^3}{\pi R^4}$ $\bar{q}$ = NORMAL LOAD, TONS/FT $R^2 = x^2 + z^2$	

VERTICAL STRESS INCREASE ($\Delta\sigma$) IN SOILS (REVIEW)

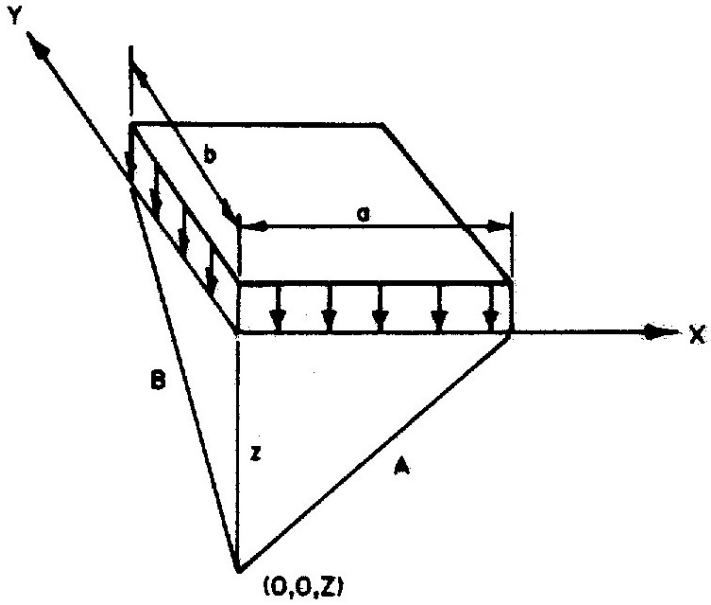
Table C-1. Boussinesq Solutions (EM 1110-1-1904).

STRIP	$\frac{q}{\pi}(\alpha + \sin\alpha \cos(\alpha + 2\beta))$ q = CONTACT PRESSURE, TSF $\alpha = \tan^{-1}\left(\frac{x+b}{z}\right) - \beta$, RADIANS $\beta = \tan^{-1}\left(\frac{x-b}{z}\right)$, RADIANS
AREA (POINT UNDER CENTER CIRCULAR AREA)	$\frac{qr^2(S^2 + 2z^2)}{2S^4}$ $S^2 = r^2 + z^2$ q = CONTACT PRESSURE, TSF



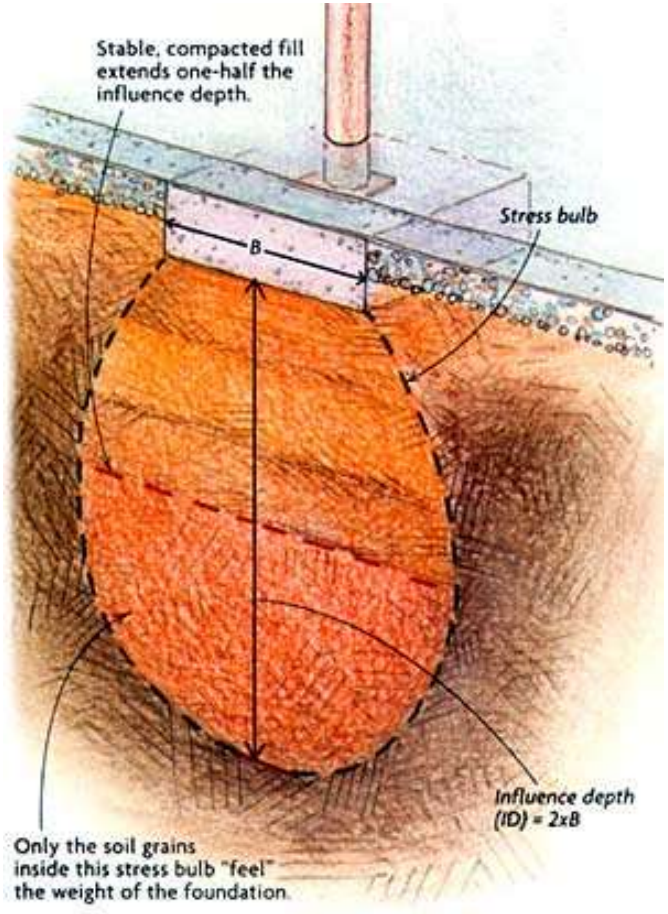
VERTICAL STRESS INCREASE ($\Delta\sigma$) IN SOILS (REVIEW)

Table C-1. Boussinesq Solutions (EM 1110-1-1904).

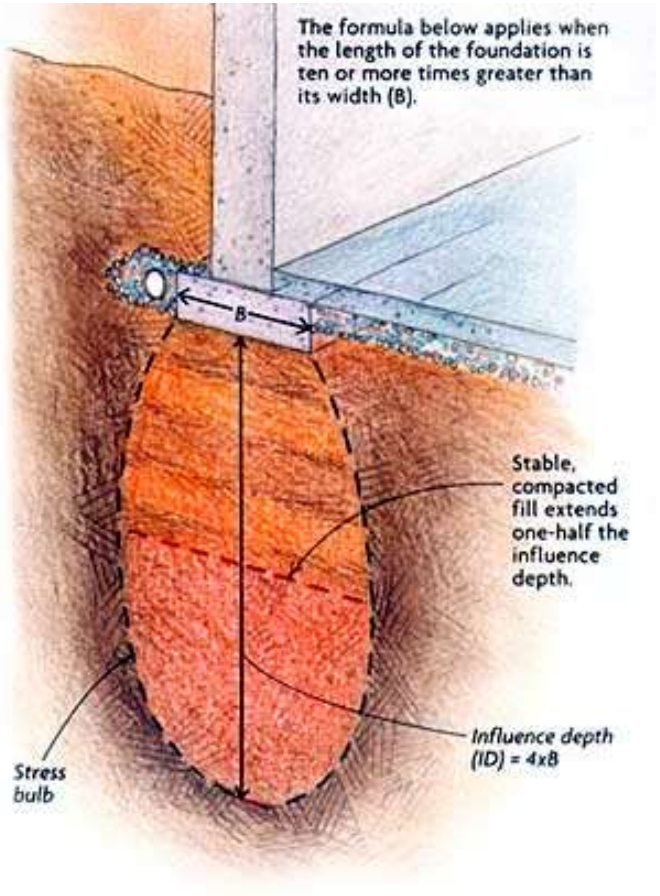
TYPE OF LOAD NORMAL TO SURFACE	EQUATION FOR $\Delta\sigma_z$	COORDINATE SYSTEM
(POINT UNDER CORNER RECTANGULAR AREA)	$\frac{q}{2\pi}\left[\text{TAN}^{-1}\frac{a\,b}{z\,C}+\frac{a\,b\,z}{C}\left(\frac{1}{A^2}+\frac{1}{B^2}\right)\right]$ $A^2 = a^2 + z^2$ $B^2 = b^2 + z^2$ $C = (a^2 + b^2 + z^2)^{1/2}$ q = CONTACT PRESSURE, TSF	

VERTICAL STRESS INCREASE ($\Delta\sigma$) IN SOILS

Depth of Influence of $\Delta\sigma$ for Settlement Calculations



SQUARE: Depth = 2B

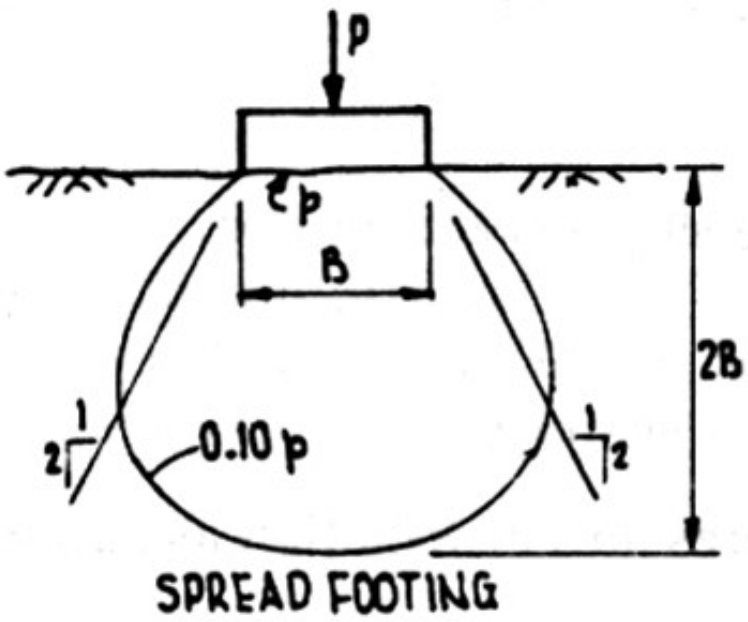


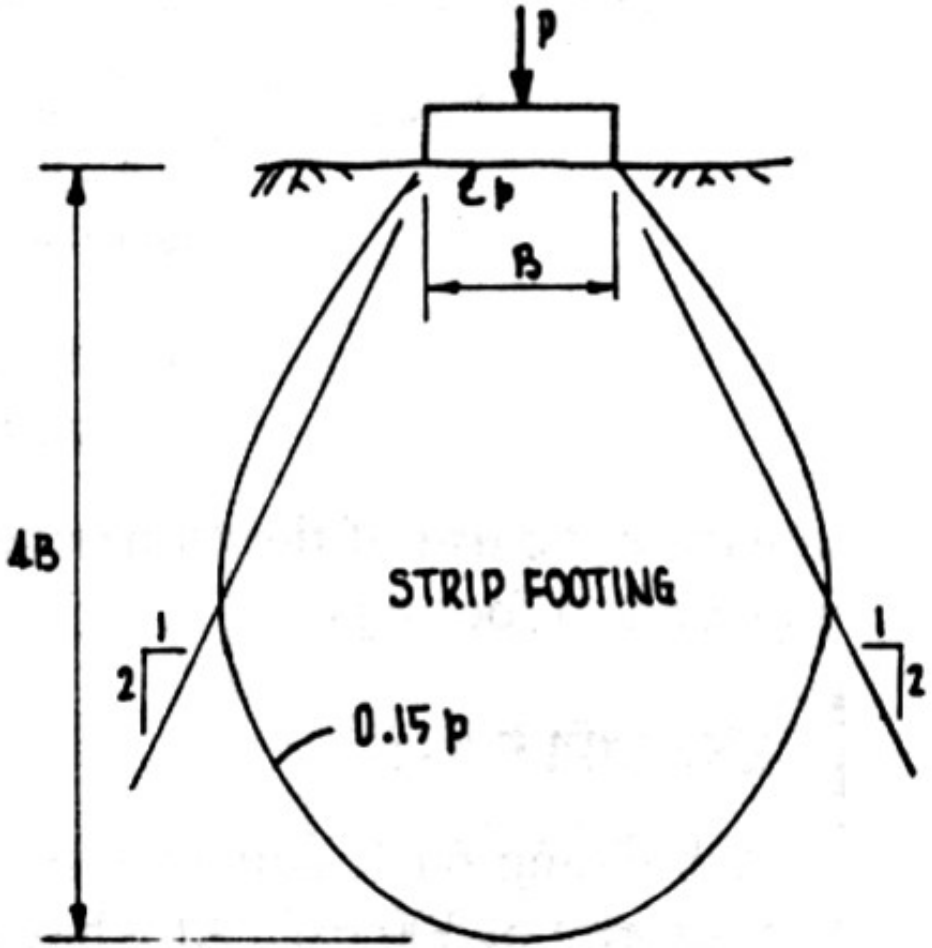
STRIP: Depth = 4B

Figures courtesy of http://www.taunton.com

VERTICAL STRESS INCREASE ($\Delta\sigma$) IN SOILS

Depth of Influence of $\Delta\sigma$ for Settlement Calculations





ELASTIC SETTLEMENT OF SOIL

General Elastic Relation (Flexible Foundation):

$$S_e = q_o(\alpha B')\frac{1-\mu_s^2}{E_s} I_s I_f$$

Where:

S_e = Elastic Settlement
q_o = Contact Stress
α = Foundation Location Factor
for Settlement under Center
α = 1, m' = L/B, n' = H/(B/2)
For Settlement under Corner
α = 1, M' = L/B, n' = H/B
B' = Width
use B for Settlement @ Corner
use B/2 for Settlement @ Center

μ_s = Soil Poisson's Ratio
E_s = Soil Elastic Modulus
I_s = Shape Factor
f(μ_s, F_1, F_2) – Table 12.3 Das FGE (2005)

$$I_s = F_1 + \frac{1-2\mu_s}{1-\mu_s} F_2$$

I_f = Depth Factor
f(D_f/B, μ_s, L/B) – Table 12.4 Das FGE (2005)

General Elastic Relation (Rigid Foundation):

$$S_e \approx 0.93 S_{e(\,flexible,center)}$$

ELASTIC SETTLEMENT OF SOIL – TABLE 12.3 Das (2005)

	m′																			
n′	1.0	1.2	1.4	1.6	1.8	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0	9.0	10.0	25.0	50.0	100.0
0.5																				
F_1	0.049	0.046	0.044	0.042	0.041	0.040	0.038	0.038	0.037	0.037	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
F_2	0.074	0.077	0.080	0.081	0.083	0.084	0.085	0.086	0.087	0.087	0.087	0.087	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088
0.8																				
F_1	0.104	0.100	0.096	0.093	0.091	0.089	0.086	0.084	0.083	0.082	0.081	0.081	0.080	0.080	0.080	0.079	0.079	0.079	0.079	0.079
F_2	0.083	0.090	0.095	0.098	0.101	0.103	0.107	0.109	0.110	0.111	0.112	0.112	0.113	0.113	0.113	0.113	0.114	0.114	0.114	0.114
1.0																				
F_1	0.142	0.138	0.134	0.130	0.127	0.125	0.121	0.118	0.116	0.115	0.114	0.113	0.112	0.112	0.112	0.111	0.111	0.110	0.110	0.110
F_2	0.083	0.091	0.098	0.102	0.106	0.109	0.114	0.117	0.119	0.120	0.121	0.122	0.123	0.123	0.124	0.124	0.124	0.125	0.125	0.125
2.0																				
F_1	0.285	0.290	0.292	0.292	0.291	0.289	0.284	0.279	0.275	0.271	0.269	0.267	0.264	0.262	0.261	0.260	0.259	0.257	0.256	0.256
F_2	0.064	0.074	0.083	0.090	0.097	0.102	0.114	0.121	0.127	0.131	0.134	0.136	0.139	0.141	0.143	0.144	0.145	0.147	0.147	0.148
4.0																				
F_1	0.408	0.431	0.448	0.460	0.469	0.476	0.484	0.487	0.486	0.484	0.482	0.479	0.474	0.470	0.466	0.464	0.462	0.453	0.451	0.451
F_2	0.037	0.044	0.051	0.057	0.063	0.069	0.082	0.093	0.102	0.110	0.116	0.121	0.129	0.135	0.139	0.142	0.145	0.154	0.155	0.156
6.0																				
F_1	0.457	0.489	0.514	0.534	0.550	0.563	0.585	0.598	0.606	0.609	0.611	0.610	0.608	0.604	0.601	0.598	0.595	0.579	0.576	0.575
F_2	0.026	0.031	0.036	0.040	0.045	0.050	0.060	0.070	0.079	0.087	0.094	0.101	0.111	0.120	0.126	0.131	0.135	0.153	0.157	0.157
8.0																				
F_1	0.482	0.519	0.549	0.573	0.594	0.611	0.643	0.664	0.678	0.688	0.694	0.697	0.700	0.700	0.698	0.695	0.692	0.672	0.666	0.665
F_2	0.020	0.023	0.027	0.031	0.035	0.038	0.047	0.055	0.063	0.071	0.077	0.084	0.095	0.104	0.112	0.118	0.124	0.151	0.156	0.158
10.0																				
F_1	0.498	0.537	0.570	0.597	0.621	0.641	0.679	0.707	0.726	0.740	0.750	0.758	0.766	0.770	0.770	0.770	0.768	0.745	0.738	0.735
F_2	0.016	0.019	0.022	0.025	0.028	0.031	0.038	0.046	0.052	0.059	0.065	0.071	0.082	0.091	0.099	0.106	0.112	0.147	0.156	0.158
12.0																				
F_1	0.508	0.550	0.585	0.614	0.639	0.661	0.704	0.736	0.760	0.777	0.791	0.801	0.815	0.823	0.826	0.828	0.828	0.806	0.796	0.793
F_2	0.013	0.016	0.018	0.021	0.024	0.026	0.032	0.038	0.044	0.050	0.056	0.061	0.071	0.080	0.088	0.095	0.102	0.143	0.154	0.158
100.0																				
F_1	0.555	0.605	0.649	0.688	0.722	0.753	0.819	0.872	0.918	0.956	0.990	1.020	1.072	1.114	1.150	1.182	1.209	1.408	1.489	1.499
F_2	0.002	0.002	0.002	0.003	0.003	0.003	0.004	0.005	0.006	0.006	0.007	0.008	0.010	0.011	0.013	0.014	0.016	0.039	0.071	0.113
1,000.0																				
F_1	0.560	0.612	0.657	0.697	0.733	0.765	0.833	0.890	0.938	0.979	1.016	1.049	1.106	1.154	1.196	1.233	1.266	1.548	1.752	1.941
F_2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.004	0.008	0.016

*After Bowles (1987)

Center of Footing: $m' = \frac{L}{B}; n' = \frac{H}{(B/2)}$

Corner of Footing: $m' = \frac{L}{B}; n' = \frac{H}{B}$

H = Depth to rigid layer

ELASTIC SETTLEMENT OF SOIL – TABLE 12.4 Das (2005)

	L/B						
D_f/B	1.0	1.2	1.4	1.6	1.8	2.0	5.0
Poisson's Ratio = 0.00 = μ_s							
0.05	0.950	0.954	0.957	0.959	0.961	0.963	0.973
0.10	0.904	0.911	0.917	0.922	0.925	0.928	0.948
0.20	0.825	0.838	0.847	0.855	0.862	0.867	0.903
0.40	0.710	0.727	0.740	0.752	0.761	0.769	0.827
0.60	0.635	0.652	0.666	0.678	0.689	0.698	0.769
0.80	0.585	0.600	0.614	0.626	0.637	0.646	0.723
1.00	0.549	0.563	0.576	0.587	0.598	0.607	0.686
2.00	0.468	0.476	0.484	0.492	0.499	0.506	0.577
Poisson's Ratio = 0.10 = μ_s							
0.05	0.958	0.962	0.965	0.967	0.968	0.970	0.978
0.10	0.919	0.926	0.930	0.934	0.938	0.940	0.957
0.20	0.848	0.859	0.868	0.875	0.881	0.886	0.917
0.40	0.739	0.755	0.768	0.779	0.788	0.795	0.848
0.60	0.665	0.682	0.696	0.708	0.718	0.727	0.793
0.80	0.615	0.630	0.644	0.656	0.667	0.676	0.749
1.00	0.579	0.593	0.606	0.618	0.628	0.637	0.714
2.00	0.496	0.505	0.513	0.521	0.528	0.535	0.606
Poisson's Ratio = 0.30 = μ_s							
0.05	0.979	0.981	0.982	0.983	0.984	0.985	0.990
0.10	0.954	0.958	0.962	0.964	0.966	0.968	0.977
0.20	0.902	0.911	0.917	0.923	0.927	0.930	0.951
0.40	0.808	0.823	0.834	0.843	0.851	0.857	0.899
0.60	0.738	0.754	0.767	0.778	0.788	0.796	0.852
0.80	0.687	0.703	0.716	0.728	0.738	0.747	0.813
1.00	0.650	0.665	0.678	0.689	0.700	0.709	0.780
2.00	0.562	0.571	0.580	0.588	0.596	0.603	0.675

ELASTIC SETTLEMENT OF SOIL – TABLE 12.4 Das (2005)

	L/B						
D_f/B	1.0	1.2	1.4	1.6	1.8	2.0	5.0
Poisson's Ratio = 0.40 = μ_s							
0.05	0.989	0.990	0.991	0.992	0.992	0.993	0.995
0.10	0.973	0.976	0.978	0.980	0.981	0.982	0.988
0.20	0.932	0.940	0.945	0.949	0.952	0.955	0.970
0.40	0.848	0.862	0.872	0.881	0.887	0.893	0.927
0.60	0.779	0.795	0.808	0.819	0.828	0.836	0.886
0.80	0.727	0.743	0.757	0.769	0.779	0.788	0.849
1.00	0.689	0.704	0.718	0.730	0.740	0.749	0.818
2.00	0.596	0.606	0.615	0.624	0.632	0.640	0.714
Poisson's Ratio = 0.50 = μ_s							
0.05	0.997	0.997	0.998	0.998	0.998	0.998	0.999
0.10	0.988	0.990	0.991	0.992	0.993	0.993	0.996
0.20	0.960	0.966	0.969	0.972	0.974	0.976	0.985
0.40	0.886	0.899	0.908	0.916	0.922	0.926	0.953
0.60	0.818	0.834	0.847	0.857	0.866	0.873	0.917
0.80	0.764	0.781	0.795	0.807	0.817	0.826	0.883
1.00	0.723	0.740	0.754	0.766	0.777	0.786	0.852
2.00	0.622	0.633	0.643	0.653	0.662	0.670	0.747

*After Bowles (1987)

ELASTIC PARAMETERS OF SOIL

Table 12.5. Typical Elastic Parameters of Soils (Das FGE (2005)

Type of soil	Modulus of elasticity, E_s (MN/m^2)	Poisson's ratio, μ_s
Loose sand	10–25	0.20–0.40
Medium dense sand	15–30	0.25–0.40
Dense sand	35–55	0.30–0.45
Silty sand	10–20	0.20–0.40
Sand and gravel	70–170	0.15–0.35
Soft clay	4–20	
Medium clay	20–40	0.20–0.50
Stiff clay	40–100	

Table D-3. Typical Soil Elastic Moduli (EM1110-1-1904)

Soil	E_s, tsf
Clay	
Very soft clay	5 - 50
Soft clay	50 - 200
Medium clay	200 - 500
Stiff clay, silty clay	500 - 1000
Sandy clay	250 - 2000
Clay shale	1000 - 2000
Sand	
Loose sand	100 - 250
Dense sand	250 - 1000
Dense sand and gravel	1000 - 2000
Silty sand	250 - 2000

ELASTIC SETTLEMENT OF SOIL (AASHTO, 2010)

Elastic Half-Space Method:

$$S_e = \frac{q_o(1-\nu^2)\sqrt{A'}}{144 E_s \beta_z}$$

Where:

S_e = Elastic Settlement
q_o = Applied Vertical Stress (ksf)
A' = Effective Area of Footing (ft^2)
E_s = Young's Modulus of Soil (ksi)
(See Article 10.4.6.3 if direct measurements are not available)

ν = Soil Poisson's Ratio
(See Article 10.4.6.3 if direct measurements are not available)
β_z = Shape Factor (dimensionless)
(As specified in Table 10.6.2.4.2-1)

Unless E_s varies significantly with depth, E_s should be determined at a depth of about ½ to 2/3 of B below the footing. If the soil modulus varies significantly with depth, a weighted average value of E_s should be used.

ELASTIC SETTLEMENT OF SOIL - DMT

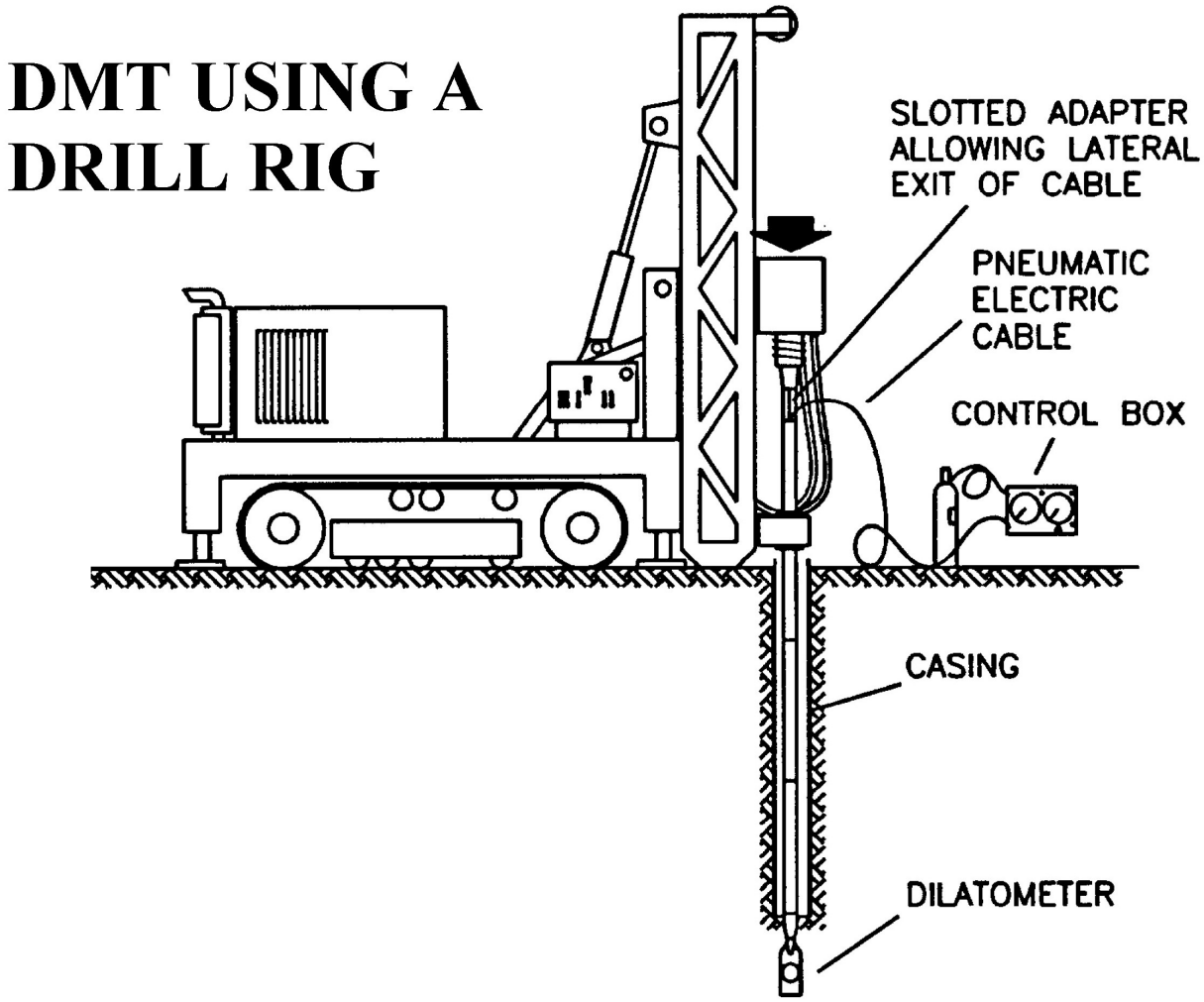


Figure courtesy of Marchetti (1999) - The Flat Dilatometer (DMT) and It's Applications to Geotechnical Design

Uses Direct Measurement of Soil to Calculate Settlement

ELASTIC SETTLEMENT OF SOIL - DMT

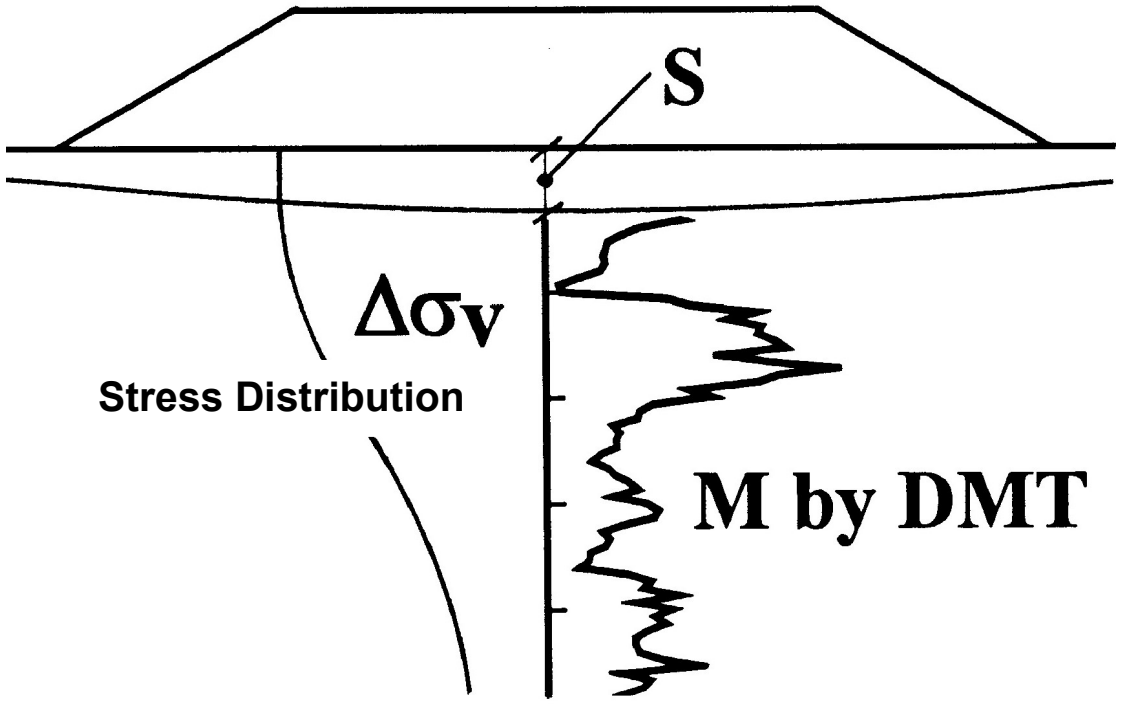


Figure courtesy of Marchetti (1999) - The Flat Dilatometer (DMT) and It's Applications to Geotechnical Design

$$S_e = \sum \frac{\Delta\sigma}{M_{DMT}} \Delta Z$$

Where:

S_e = Elastic Settlement
$\Delta\sigma$ = Change in Stress
M_{DMT} = Constrained Modulus
Z = Depth

ELASTIC SETTLEMENT OF SOIL - DMT

K_0	Coeff. Earth Pressure in Situ	$K_{0,DMT} = (K_D / 1.5)^{0.47} - 0.6$
OCR	Overconsolidation Ratio	$OCR_{DMT} = (0.5\ K_D)^{1.56}$
c_u	Undrained Shear Strength	$c_{u,DMT} = 0.22\ \sigma'_{v0}\ (0.5\ K_D)^{1.25}$
Φ	Friction Angle	$\Phi_{safe,DMT} = 28° + 14.6°\ \log K_D - 2.1°\ \log^2 K_D$
c_h	Coefficient of Consolidation	$c_{h,DMTA} \approx 7\ cm^2 / t_{flex}$
k_h	Coefficient of Permeability	$k_h = c_h\ \gamma_w / M_h\ \ (M_h \approx K_0\ M_{DMT})$
γ	Unit Weight and Description	(see chart in Fig. 16)
M	Vertical Drained Constrained Modulus	$M_{DMT} = R_M\ E_D$ if $I_D \le 0.6$ $R_M = 0.14 + 2.36 \log K_D$ if $I_D \ge 3$ $R_M = 0.5 + 2 \log K_D$ if $0.6 < I_D < 3$ $R_M = R_{M,0} + (2.5 - R_{M,0}) \log K_D$ with $R_{M,0} = 0.14 + 0.15\ (I_D - 0.6)$ if $K_D > 10$ $R_M = 0.32 + 2.18 \log K_D$ if $R_M < 0.85$ set $R_M = 0.85$
u_0	Equilibrium Pore Pressure	$u_0 = p_2 = C - Z_M + \Delta A$

Marchetti (1999) - The Flat Dilatometer (DMT) and
It's Applications to Geotechnical Design

ELASTIC SETTLEMENT OF SOIL - DMT

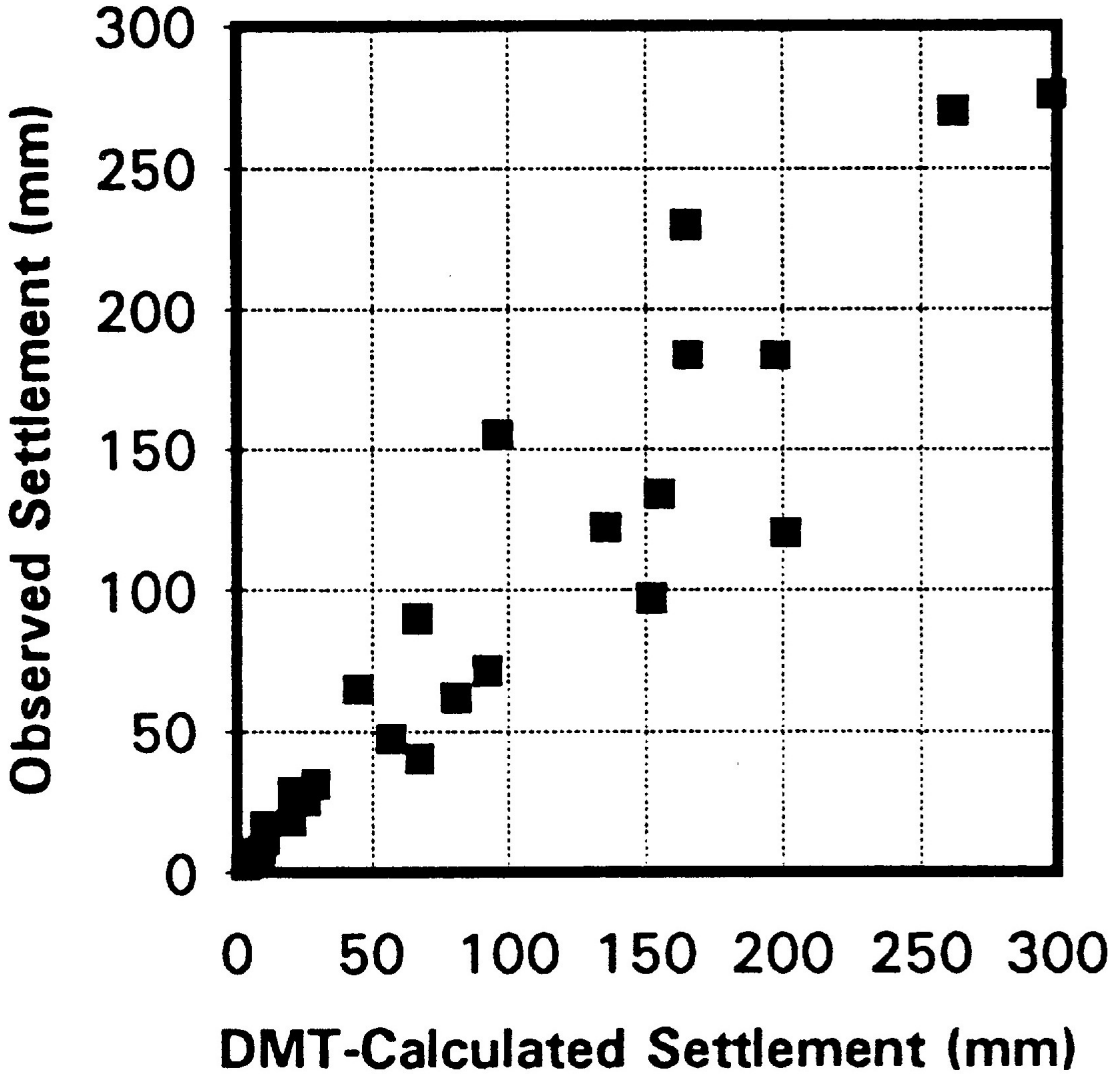
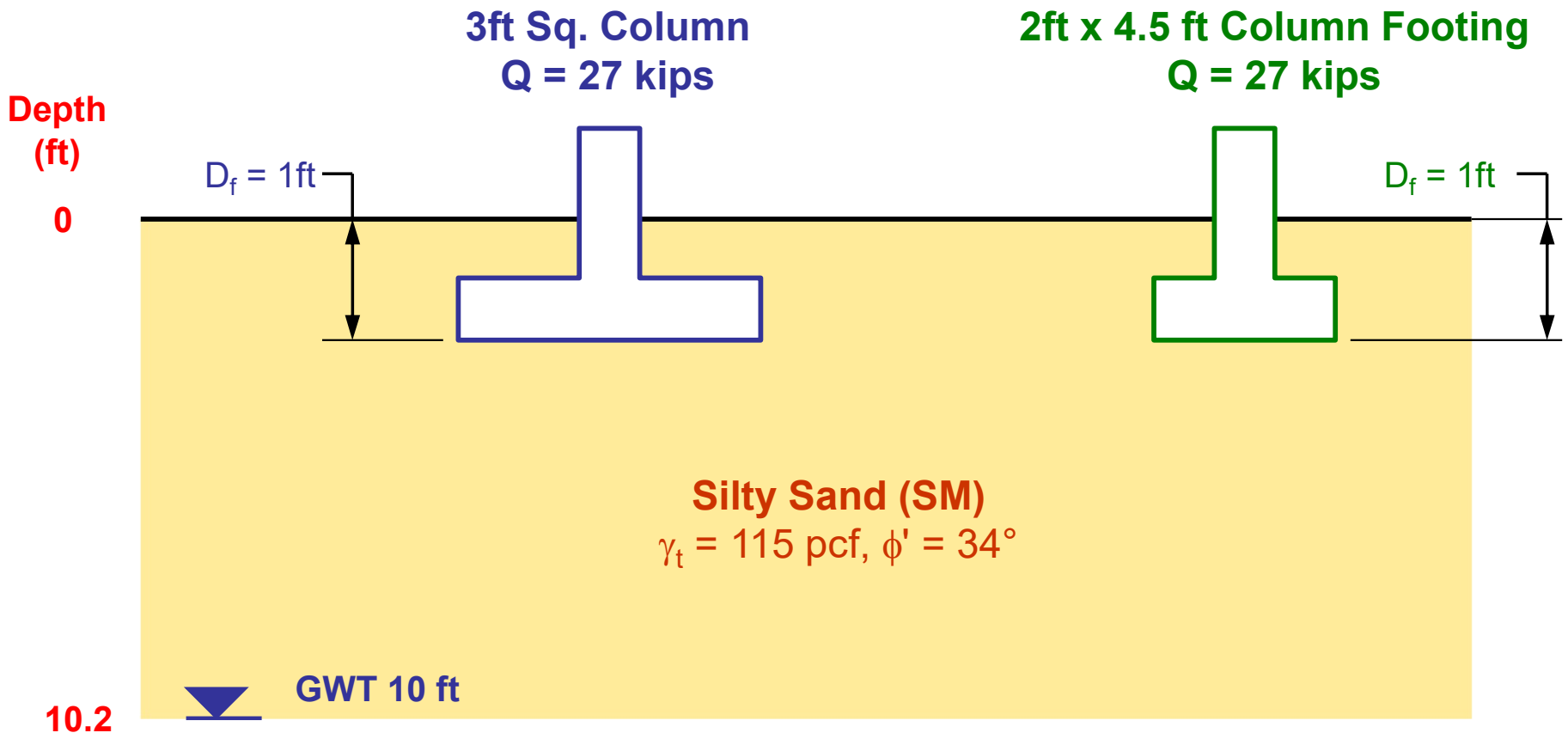


Figure from Hayes (1990)

DMT SETTLEMENT EXAMPLE (NTS)



Determine Settlement of Both Footings using the provided DMT Data

DMT SETTLEMENT EXAMPLE

DMT Data

Classification	K_D	E_D (tsf)	M (tsf)
Silty Sand	19	46	154
Silty Sand	14	49	261
Silty Sand	20	93	386
Silty Sand	13	122	275
Silty Sand	13	100	306
Silty Sand	13	111	256
Silty Sand	11	93	187
Silty Sand	9	71	263
Silty Sand	8	111	320
Silty Sand	7	144	286
Silty Sand	7	133	416
Silty Sand	8	188	483
Silty Sand	8	213	464
Silty Sand	6	202	387
Silty Sand	7	184	322
Sandy Silt	6	151	268
Sandy Silt	5	129	227
Sandy Silt	5	122	105
Clayey Silt	5	56	276
Sand	2	162	105
Sandy Silt	5	115	75
Clayey Silt	4	42	165
Sandy Silt	3	100	217
Silty Sand	4	148	150
Sandy Silt	4	97	182
Silt	5	107	88
Silty Clay	6	49	26
Clay	6	13	48
Clay	5	24	57
Clay	5	31	30

