CHAPTER 2
LIMITATIONS OF SETTLEMENT

2-1. General. Significant aspects of settlement from static and dynamic loads are total and differential settlement. Total settlement is the magnitude of downward movement. Differential settlement is the difference in vertical movement between various locations of the structure and distorts the structure. Conditions that cause settlement are described in Table 1-1. Limitations to total and differential settlement depend on the function and type of structure.

2-2. Total Settlement. Many structures can tolerate substantial downward movement or settlement without cracking, Table 2-1; however, total settlement should not exceed 2 inches for most facilities. A typical specification of total settlement for commercial buildings is 1 inch (item 35). Structures such as solid reinforced concrete foundations supporting smokestacks, silos, and towers can tolerate larger settlements up to 1 ft.

Table 2-1

Maximum Allowable Average Settlement of Some Structures
(Data from Item 53)

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

Some limitations of total settlement are as follows:

a. Utilities. Total settlement of permanent facilities can harm or sever connections to outside utilities such as water, natural gas, and sewer lines. Water and sewer lines may leak contributing to localized wetting of the soil profile and aggravating differential displacement. Leaking gas from breaks caused by settlement can lead to explosions.

b. Drainage. Total settlement reduces or interferes with drainage of surface water from permanent facilities, contributes to wetting of the soil profile with additional differential movement, and may cause the facility to become temporarily inaccessible.

c. Serviceability. Relative movement between the facility and surrounding soil may interfere with serviceability of entry ways.

d. Freeboard. Total settlement of embankments, levees and dams reduces freeboard and volume of water that may be retained. The potential for flooding is greater during periods of heavy rainfall. Such settlement also alters the grade of culverts placed under roadway embankments.

2-3. Differential Settlement. Differential settlement, which causes distortion and damages in structures, is a function of the uniformity of the soil, stiffness of the structure, stiffness of the soil, and distribution of loads within the structure. Limitations to differential settlement depend on the application. Differential settlements should not usually exceed 1/2 inch in buildings, otherwise cracking and structural damage may occur. Differential movements between monoliths of dams should not usually exceed 2 inches, otherwise leakage may become a problem. Embankments, dams, one or two story facilities, and multistory structures with flexible framing systems are sufficiently flexible such that their stiffness often need not be considered in settlement analysis. Pavements may be assumed to be completely flexible.

a. Types of Damages. Differential settlement may lead to tilting that can interfere with adjacent structures and disrupt the performance of machinery and people. Differential settlement can cause cracking in the structure, distorted and jammed doors and windows, uneven floors and stairways, and other damages to houses and buildings. Differential movement may lead to misalignment of monoliths and reduce the efficiency of waterstops. Refer to Chapter 2, EM 1110-2-2102, for guidance on selection of waterstops. Widespread cracking can impair the structural integrity and lead to collapse of the structure, particularly during earthquakes. The height of a wall for a building that can be constructed on a beam or foundation without cracking is related to the deflection/span length Δ/L ratio and the angular distortion β described below.

b. Deflection Ratio. The deflection ratio Δ/L is a measure of the maximum differential movement Δ in the span length L, Figure 2-1. The span length may be between two adjacent columns, L_{SAG} or L_{HOG}, Figure 2-1a.

(1) Table 2-2 provides limiting observed deflection ratios for some buildings.

(2) Design Δ/L ratios are often greater than 1/600, but the stiffness contributed by the components of an assembled brick structure, for example, helps maintain actual differential displacement/span length ratios near those required for brick buildings, Table 2-2, to avoid cracking.

(3) Circular steel tanks can tolerate Δ/L ratios greater than 1/200 depending on the settlement shape (item 13).

c. Angular Distortion. Angular distortion $\beta = \delta/\ell$ is a measure of Differential movement δ between two adjacent points separated by the distance ℓ, Figure 2-1.

(1) Initiation of damage. Table 2-3 illustrates limits to angular distortion for various types of structures without cracking based on field surveys of damage.

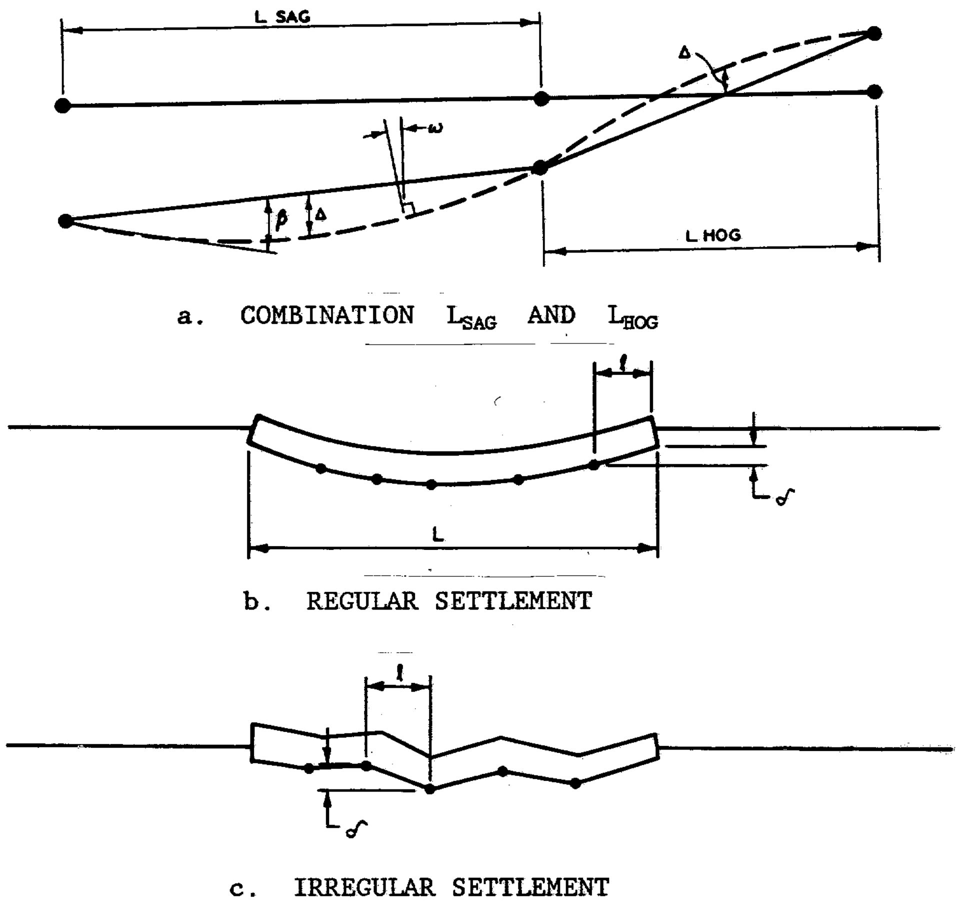

Figure 2-1. Schematic illustration of angular distortion $\beta = \delta/\ell$ and deflection ratio Δ/L for settling (sagging) and heaving (hogging) profiles

Table 2-2

Some Limiting Deflection Ratios
(After Items 17, 53, 65)

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

(a) A safe limit for no cracking in properly designed and constructed steel or reinforced concrete frame structures is angular distortion β = 1/500. Cracking should be anticipated when β exceeds 1/300. Considerable cracking in panels and brick walls and structural damage is expected when β is less than 1/150.

(b) Tilting can be observed if $\omega > 1/250$ and must be limited to clear adjacent buildings, particularly in high winds. The angle of tilt is indicated by ω , Figure 2-1a.

(c) Slower rates of settlement increase the ability of structures to resist cracking.

(d) Unreinforced concrete masonry unit construction is notably brittle and cracks at relatively low angular distortion values as shown in Table 2-3. Such structures must be properly detailed and constructed to provide acceptable service at sites with even moderate differential movement potential. Consideration should be given to using a less crack-susceptible material at expansive soil sites and any other site having a significant differential movement potential.

(2) Influence of architecture. Facades, siding, and other architectural finishes are usually placed after a portion of the settlement has occurred. Most settlement, for example, may have already occurred for facilities on cohesionless soil; whereas, very little settlement may have occurred for facilities on compressible, cohesive soil when the facade is to be placed.

(a) Larger angular distortions than those shown in Table 2-3 can be accommodated if some of the settlement has occurred before installation of architectural finishes.

(b) The allowable angular distortion of the structure, Table 2-3, should be greater than the estimated maximum angular distortion of the foundation, Table 2-4, to avoid distress in the structure.

d. Estimation of the Maximum Angular Distortion. The maximum angular distortion for uniformly loaded structures on laterally uniform cohesive soil profiles occurs at the corner, Figure 2-1b. The maximum angular distortion may be estimated from the lateral distribution of calculated settlement. The maximum angular distortion for structures on sand, compacted fill, and stiff clay often occurs anywhere on the foundation because the settlement profile is usually erratic, Figure 2-1c.

(1) The maximum angular distortion at a corner of a foundation shaped in a circular arc on a uniformly loaded cohesive soil for the Boussinesq stress distribution, Appendix C, is approximately

$$\beta_{max} = \frac{3 \cdot \rho_{max}}{(N_{col} - 1) \cdot \ell} \tag{2-1}$$

where

ρ_{max} = maximum settlement in center of mat, ft
N_{col} = number of columns in a diagonal line on the foundation
ℓ = distance between adjacent columns on the diagonal line, ft

Table 2-3

Limiting Angular Distortions to Avoid
Potential Damages (Data from Items 53, 65, TM 5-818-1)

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

Table 2-4

Empirical Correlations Between Maximum Distortion (Δ) and Angular Distortion β (From Table 5-3, TM 5-818-1)

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.

The maximum settlement may be calculated from loads on soil beneath the center of the foundation using methodology of Chapter 3.

(2) When the potential for soil heave and nonuniform soil wetting exists, the maximum angular distortion may be the sum of the maximum settlement ρ_{max} without soil wetting and maximum potential heave S_{max} of wetted soil divided by the minimum distance between ρ_{max} and S_{max}. S_{max} may occur beneath the most lightly loaded part of the foundation such as the midpoint between diagonal columns. ρ_{max} may occur beneath the most heavily loaded part of the structure. ρ_{max} will normally only be the immediate elastic settlement ρ_i ; consolidation is not expected in a soil with potential for heave in situ. Nonuniform soil wetting may be caused by leaking water, sewer, and drain lines.

(3) When the potential for soil heave and uniform wetting occurs, the maximum angular distortion will be the difference between the maximum and minimum soil heave divided by the minimum distance between these locations. The maximum and minimum heave may occur beneath the most lightly and heavily loaded parts of the structure, respectively. Uniform wetting may occur following construction of the foundation through elimination of evapotranspiration from the ground surface.

(4) When the potential for soil collapse exists on wetting of the subgrade, the maximum angular distortion will be the difference between the maximum settlement of the collapsible soil ρ_{col} and ρ_{min} divided by the distance between these points or adjacent columns. ρ_{min} may be the immediate settlement assuming collapse does not occur (no soil wetting) beneath a point. See Chapter 5 for further details on heaving and collapsing soil and Sections I and II of Chapter 3 for details on calculating immediate settlement.

e. Correlations between Deflection Ratio and Angular Distortion. The deflection ratio Δ/L may be estimated from the maximum angular distortion or slope at the support by (item 65)

$$\frac{\Delta}{L} = \frac{\beta}{3} \bullet \left[\frac{1 + 3.9(H_w/L)^2}{1 + 2.6(H_w/L)^2}\right] \qquad (2\text{-}2)$$

where

Δ = differential displacement, ft
L = span length or length between columns, ft
H_w = wall height, ft
β = angular distortion

The deflection ratio Δ/L is approximately 1/3 of the angular distortion β for short, long structures or L/H_w greater than 3.

(1) Table 2-4 illustrates empirical correlations between the maximum deflection Δ and angular distortion β for uniformly loaded mats and spread footings on homogeneous sands, silts, and clays.

(2) Figure 2-2 illustrates a relationship between the allowable differential settlement Δ_a, column spacing L, and the angular distortion β.

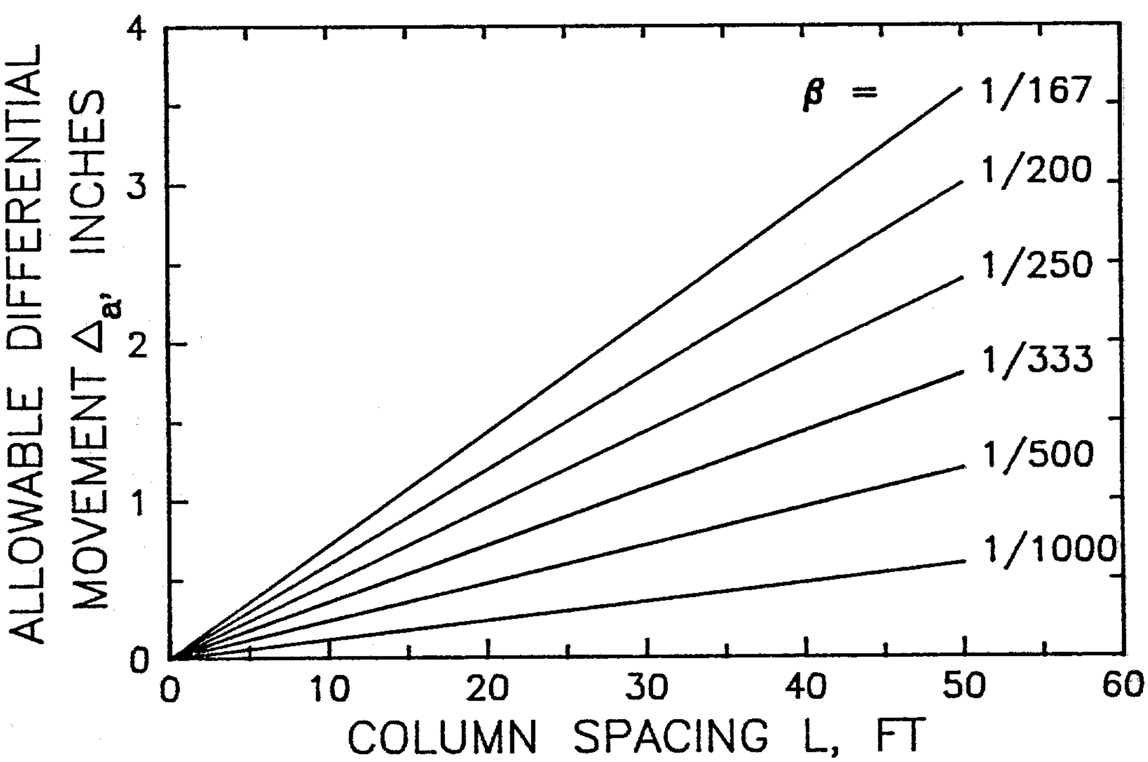

Figure 2-2. Allowable differential movement for buildings
(After Navfac DM-7.1)