CHAPTER 5 – CAPACITIES OF DRILLED SHAFTS WITH ANOMALIES

Drilled shaft capacity is the lesser of two capacities: structural capacity and geotechnical capacity. The structural capacity is the drilled shaft's material strength without the interference of foundation soils; and the geotechnical capacity involves the subsurface geological materials, soils and rocks, in supporting design loads. Typically, the structural capacity is higher than the geotechnical capacity, but not always, particularly when a drilled shaft contains anomalies. This chapter presents finite element analyses results of structural and geotechnical capacities of drilled shafts with anomalies. To incorporate the effects of various factors including subsoil types (granular and clayey soils), locations of anomalies, shaft diameters, and shapes of anomalies, nearly 400 analyses were performed as demonstrated in the later sections.

5.1. STRUCTURAL CAPACITY OF DRILLED SHAFTS

5.1.1 Concrete

Concrete strength was modeled using the Mohr-Coulomb model. This allowed the evaluation of the structural capacity of drilled shafts with anomalies. The Mohr-Coulomb material parameters for concrete are summarized in Table 11. The resulting stress strain relationship from the finite element analyses of two concrete cylinders with diameters of 1 m and 2 m and different uniaxial strengths of 20.7 and 31.1 MPa are shown in Figure 56.

Table 11. Properties of Concrete.

Number	28-day compressive strength (kPa)	Young's modulus (kPa)	Poisson's ratio	Mohr-Coulomb friction angle (degree)	Mohr-Coulomb cohesion (kPa)
1	20,710 (3,000 psi)	21,552,265	0.2	38	4,960
2	3,1065 (4,500 psi)	26,396,026	0.2	38	7,423

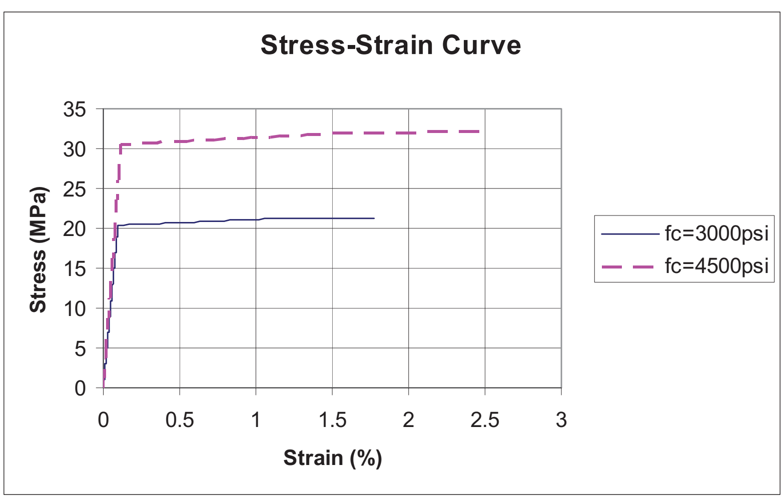


Figure 56. Stress strain curves for concrete cylinders.

5.1.2 Structural capacity of drilled shafts without anomalies via ACI Code

The structural capacities of drilled shafts with diameters of 1 m and 2 m, and a length of 20 m were evaluated using the following equations from the ACI code (ACI 318-05):

Drilled shaft with reinforcement:

$$\phi P_n = \beta\phi\left[0.85 f_c'\left(A_g - A_s\right) + A_s f_y\right] \quad \text{(Eq. 54)}$$

The capacity of concrete only:

$$\phi P_n^c = \beta\phi 0.85 f_c'\left(A_g - A_s\right) \quad \text{(Eq. 55)}$$

The capacity of the shaft without reinforcement:

$$P_n^c = \beta 0.85 P^c \quad \text{(Eq. 56)}$$

where:

$$P^c = f_c' A_g \quad \text{(Eq. 57)}$$

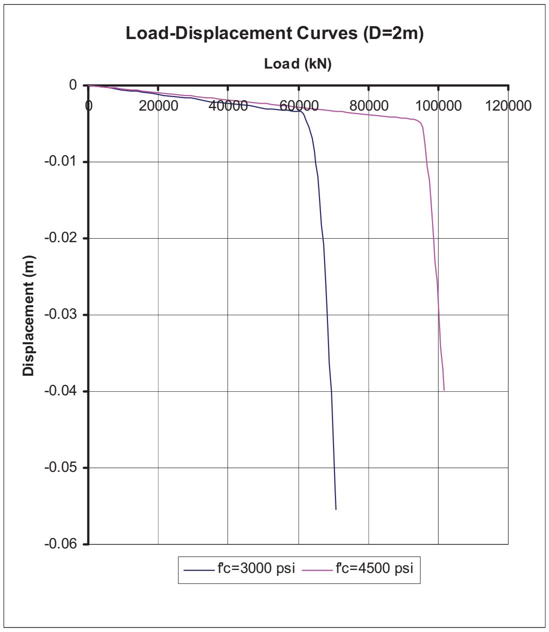
Additionally, finite element analyses were performed on the above four drilled shafts on rigid support (or hard rocks). The resulting load-displacement curves are shown in Figure 57 where the displacements reflect the elastic deformation of drilled shafts under load. The structural capacity of drilled shafts with 2% of reinforcement is given in Table 13, in which ϕ and β factor is rejected.

Table 12. Structural capacity of concrete without reduction.

Concrete Strength, f_c' kPa (psi)	Shaft Diameter (m)	P^c, Eq. 57 (kN)	P^c, FEM (kN)
20,710 (3,000)	2	65,062.0	64,687.14
31,065 (4500)	2	97,594.0	98,570.88
20,710 (3000)	1	16,265.5	16,017.77
31,065 (4500)	1	24,398.5	24,642.72

Table 13. Structural capacity of drilled shafts with 2% reinforcement

Concrete Strength, f_c' kPa (psi)	Shaft Diameter (m)	P_n/β (kN)
20,710 (3,000)	2	80,214
31,065 (4500)	2	107,313
20,710 (3000)	1	19,931
31,065 (4500)	1	26,708



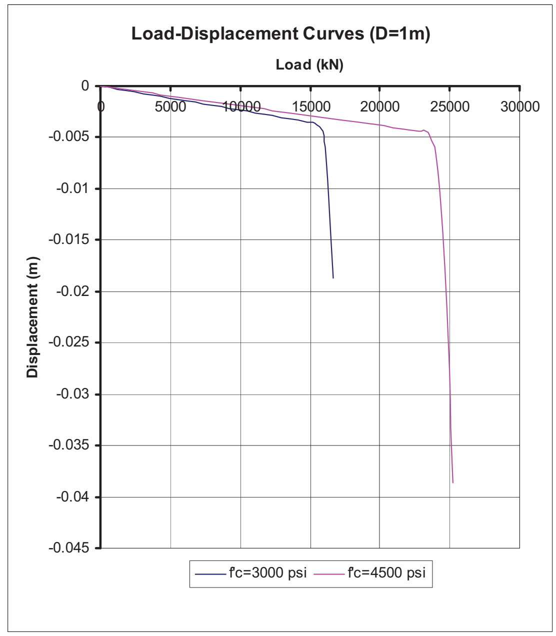


Figure 57. Load-displacement curves of four concrete drilled shafts.

5.2. STRUCTURAL CAPACITY OF DRILLED SHAFTS WITH ANOMALIES

5.2.1 Size, location, and properties of anomalies

Hypothetical drilled shafts with various sizes of anomalies located at different elevations within the shafts shown in Figure 58, Table 14, and Table 15, and their sizes and shapes are shown in Figure 59. All anomalies discussed were concentric anomalies except the last one, a nonconcentric anomaly. As discussed later, this nonconcentricity had a drastic effect on the structural capacity of a drilled shaft. The created lengths of anomalies were 0.2 m, 1 m, and 1.2 m. Table 14 summarizes the types of anomalies and the associated cross-sectional area reductions.

For the drilled shafts with neck-in types 1, 2, or 3, the reinforcements are not covered with concrete; thus their structural capacities are assumed to be the same as the drilled shafts without reinforcement. For the drilled shafts with cubic and nonconcentric anomalies, the structural capacities include the contributions from both concrete and 2% reinforcement; but only the reinforcement covered by concrete in nonconcentric anomalies was considered.

Table 14. Anomaly sizes.

Shaft Diameter (m)	Shape	Area (m^2)	Reduction of Cross Section (%)
2	Cubic 0.93 x 0.93	0.865	27.5
2	Cylinder R_d = 0.88	2.430	77.3
2	Neck-in type 1	2.440	77.3
2	Neck-in type 2	2.760	87.7
2	Neck-in type 3	3.050	96.7
2	Nonconcentric	2.440	77.3
1	Cubic 0.465 x 0.465	0.216	27.5
1	Cylinder R_d = 0.44	0.604	77.3
1	Neck-in type 1	0.610	77.3
1	Neck-in type 2	0.690	87.7
1	Neck-in type 3	0.763	96.7
1	Nonconcentric	0.604	77.3

Table 15. Anomaly locations.

Number	Depth (m)
1	1
2	11
3	19

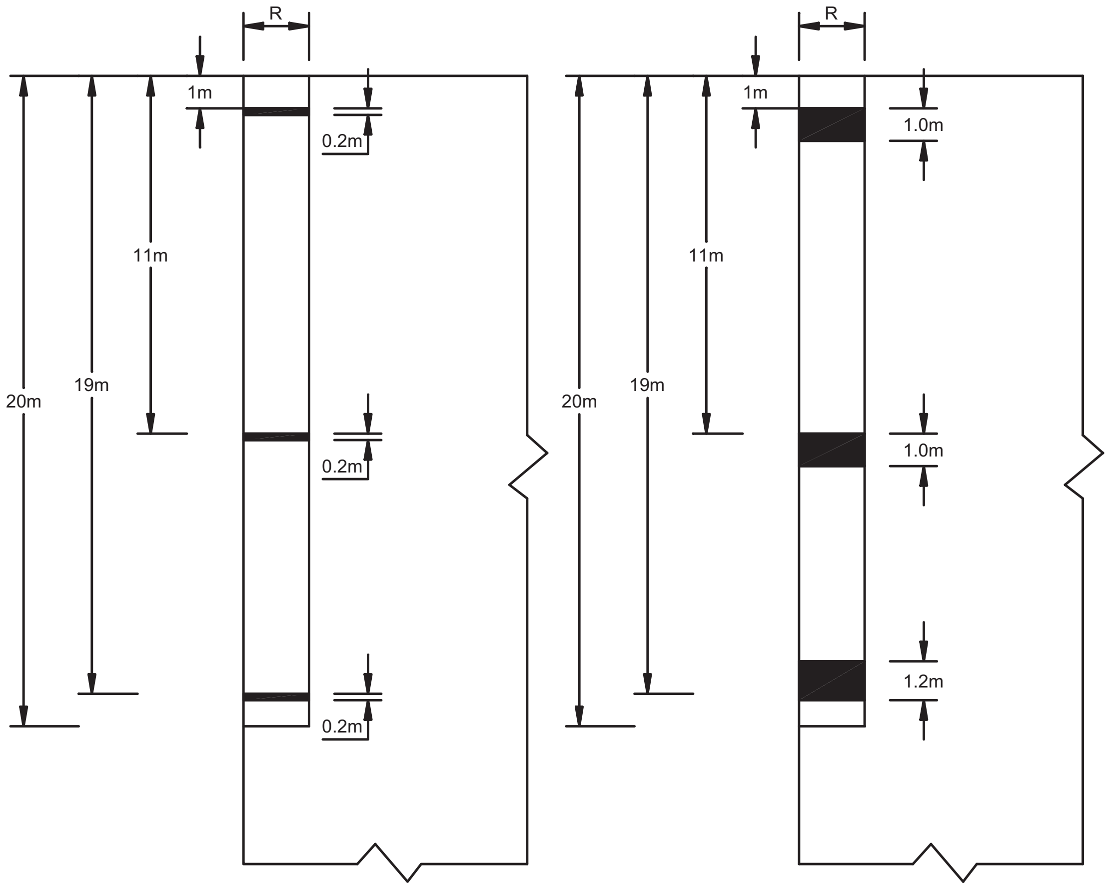


Figure 58. Anomaly locations.

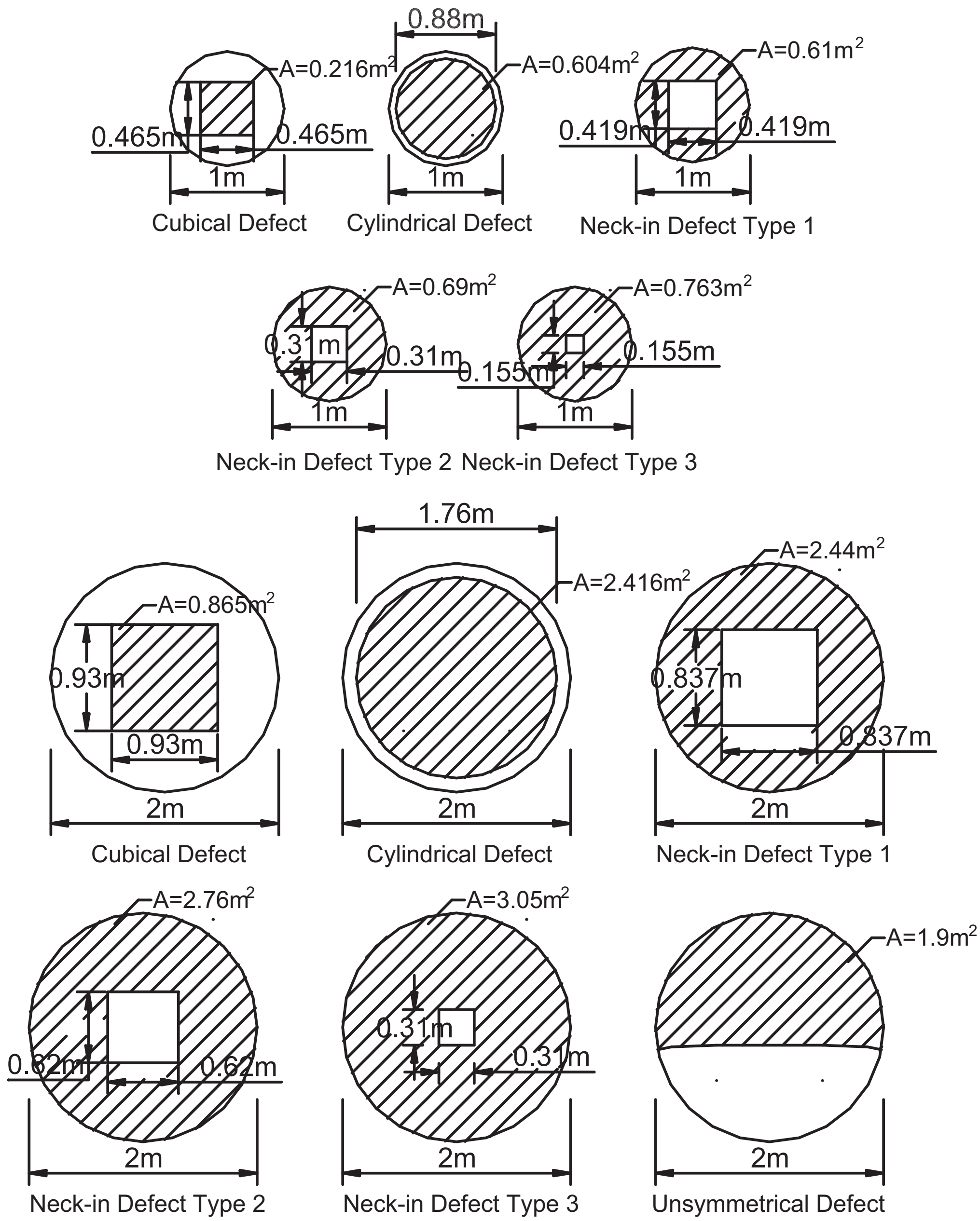


Figure 59. Anomaly sizes and shapes (shaded areas are anomaly zones).

5.2.2 Structural capacity of drilled shafts with anomalies

Structural capacities of drilled shafts with anomalies are represented in Table 16 for sections with concrete only and sections with concrete and 2% reinforcement. For anomaly sections with concrete only, structural capacities are computed using the values in Table 12. For cubical sections with 2% reinforcement, the structural capacities are computed using the values from Table 13. For drilled shafts with nonconcentric sections, the structural capacity for the axial load only or for the axial load and the bending moment can be calculated using the finite element analysis and interaction diagram, created using the method represented in Chapter 3. As shown in Figure 60, the point representing the structural capacity for axial load and bending moment (P and M = 0.51P, where e = 0.51 m is eccentricity) of drilled shafts with nonconcentric anomalies computed by finite element analysis lies nearly on the interaction curve.

Table 16. Structural capacities of drilled shafts with anomalies.

Concrete Strength kPa (psi)	Anomaly type	% Area Reduction (% Capacity Reduction)	Structural Capacity (kN)	
			(D = 2 m)	(D = 1m)
20,710 (3,000)	Cubical	27.5	46898	11613.0
	Cylindrical	77.3	14769	3692.0
	Neck-in type 1	77.3	14769	3692.0
	Neck-in type 2	87.7	8003	2001.0
	Neck-in type 3	96.7	2147	536.8
31,065 (4,500)	Cubical	27.5	71464	17866.0
	Cylindrical	77.3	22154	5538.0
	Neck-in type 1	77.3	22154	5538.0
	Neck-in type 2	87.7	12004	3001.0
	Neck-in type 3	96.7	3220	805.0

Table 16. (continued).

Concrete Strength kPa (psi)	Anomaly type	% Area Reduction	% Capacity Reduction	Structural Capacity (2% of reinforcement) (kN)	
				(D = 2 m)	(D = 1 m)
20,710 (3,000)	Cubical	27.5	19.1	64,867	16,117
	Nonconcentric (1)	77.3	87.7	9,857	-
	Nonconcentric (2)	77.3	58.8	33,070	-
31,065 (4,500)	Cubical	27.5	21.6	84,293	20,989
	Nonconcentric (1)	77.3	89.1	11,705	-
	Nonconcentric (2)	77.3	59.0	43,936	-

Note: (1) - Axial load and bending moment; (2) - Axial load only

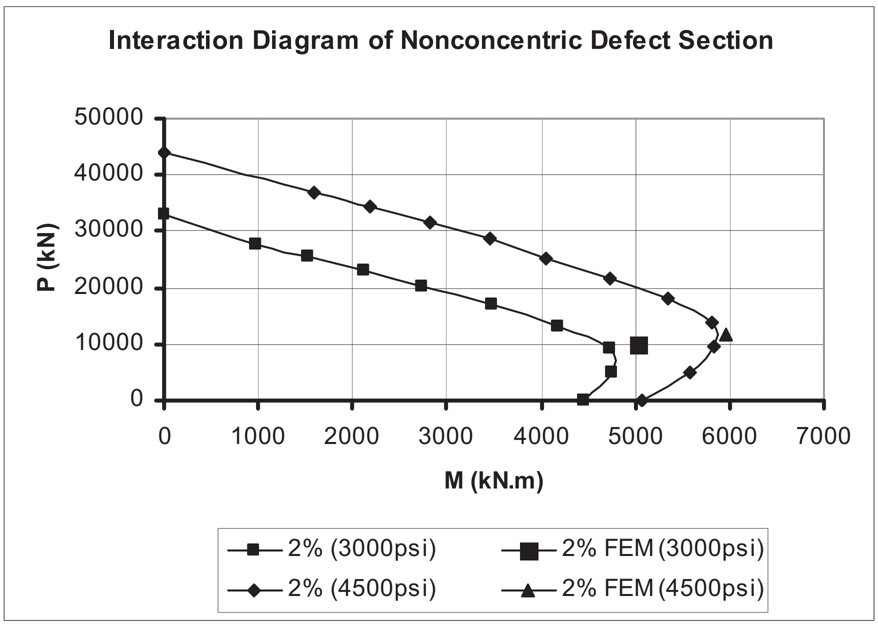


Figure 60. Structural capacity and interaction diagram of nonconcentric anomaly section.

5.3. SOIL PROPERTIES

The Mohr-Coulomb model was used to describe the behavior of the clay and sand with the former ranges from soft to stiff and the latter ranges from loose to dense. In the case of soft clay, a drilled shaft is assumed to rest on bedrock. The properties of soils are summarized in Table 17.

Table 17. Strength properties of soil.

Number	Soil type	Friction angle (^{0})	Cohesion (kPa)
1	Sand	45	0
2	Sand	40	0
3	Sand	30	0
4	Clay	0	25
5	Clay	0	50
6	Clay	0	100
7	Clay	0	200
8	Clay	0	300

Soil Young's modulus varies with depth given in the following equation:

$$E = Kp_a\left(\frac{\sigma_3}{p_a}\right)^n \qquad \text{(Eq. 58)}$$

where E Young's modulus; K Young's modulus number; n Young's modulus exponent number; σ_3 horizontal stress varies with depth; and p_a atmospheric pressure.

For the sandy soil, Young's modulus is assumed to vary linearly with depth with $n = 1$. The dilatancy angles of soils as shown in Figure 61 can be determined by (Bolton, 1986):

$$\psi = \varphi_{tc} - \varphi_{cv} = 3\left(D_r\left(10 - \ln\frac{100p}{p_a}\right) - 1\right) \qquad \text{(Eq. 59)}$$

where φ_{tc} peak secant friction angle in triaxial compression test; φ_{cv} friction angle at critical void ratio; D_r relative density; p_a atmospheric pressure; and p mean pressure. Values of φ_{tc} are equal to φ, where $\varphi = 45^0$ at $D_r = 100\%$, $\varphi = 40^0$ at $D_r = 60\%$, and $\psi = 0^0$ for $\varphi = 30^0$.

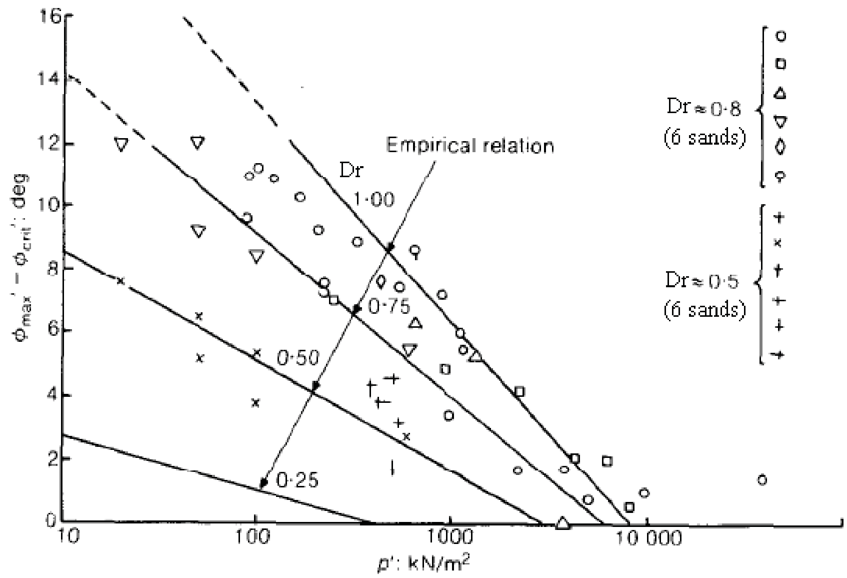


Figure 61. Dilatancy angles for sands (Bolton, 1986).

For the clay soil, Young's modulus is assumed to vary parabolically with depth and $n = 0.5$. Young's modulus does not affect the failure load of drilled shafts, for all cases, $K = 1000$. The Poisson's ratio for sand is 0.3 and for clay is 0.495. Bedrock at shaft tip in the clayey soil was modeled as an elastic material. The coefficient of lateral earth pressure at rest is assumed:

$$K_0 = 1 - \sin\varphi \qquad \text{(Eq. 60)}$$

5.4 SHAFT MODEL

The shaft is modeled by using 20-node solid elements, and reinforcement is modeled by nonlinear bar elements as represented in an earlier chapter. Under vertical load, only one-quarter of full model for symmetric anomaly and one-half of model for nonconcentric anomaly are used in analyses. The plane view and 3-D view of models are shown in Figure 62 for symmetric anomalies and Figure 63 for nonconcentric anomalies.

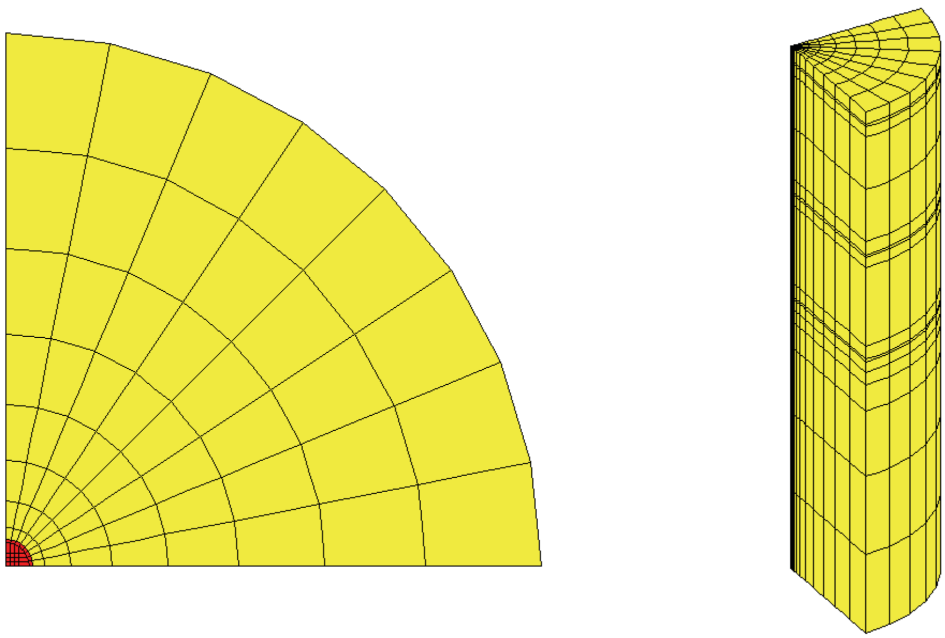


Figure 62. Plane and 3-D views of a drilled shaft with symmetric anomalies.

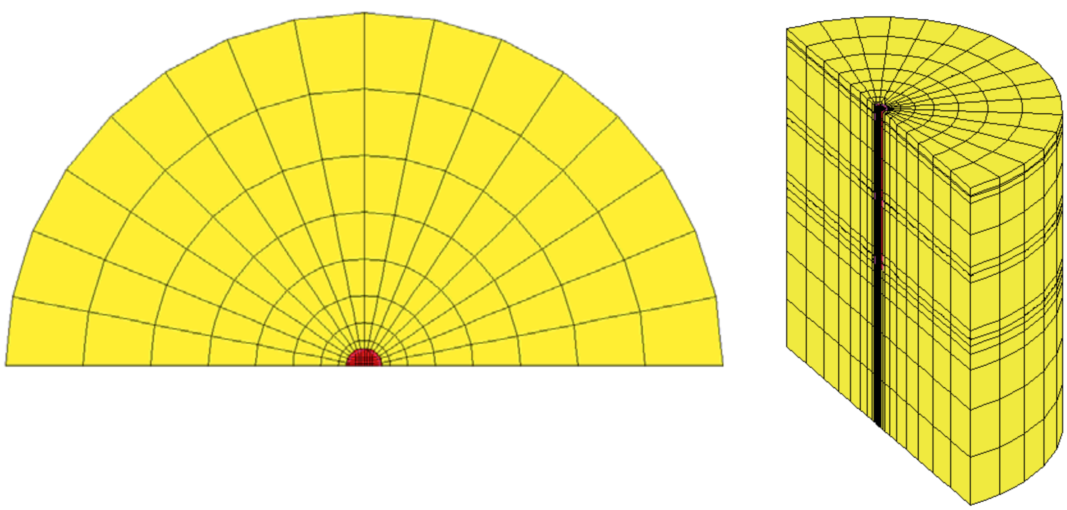


Figure 63. Plane and 3-D views of a drilled shaft with nonconcentric anomalies.

5.5 DEFINE THE EFFECT OF ANOMALIES

There are two kinds of capacities in drilled shaft design: geotechnical capacity and structural capacity. The former is the ultimate capacity of a drilled shaft for geotechnical consideration; the latter is the ultimate capacity of a drilled shaft for structural consideration. The smaller of the two controls the capacity of a drilled shaft and is further called drilled shaft capacity. When a load is applied to the top of a drilled shaft, it is transferred to both drilled shafts and its surrounding foundation soils in terms of side shear initially and eventually to both side shear and end bearing force. The total load transferred to the drilled shaft is termed “shaft-load transfer.” The total load transferred to the surrounding geomaterials is termed “geotechnical-load transfer” with an understanding that the sum of the load transferred to shaft and the load transferred to geomaterials equals the total load applied at the top of the drilled shaft.

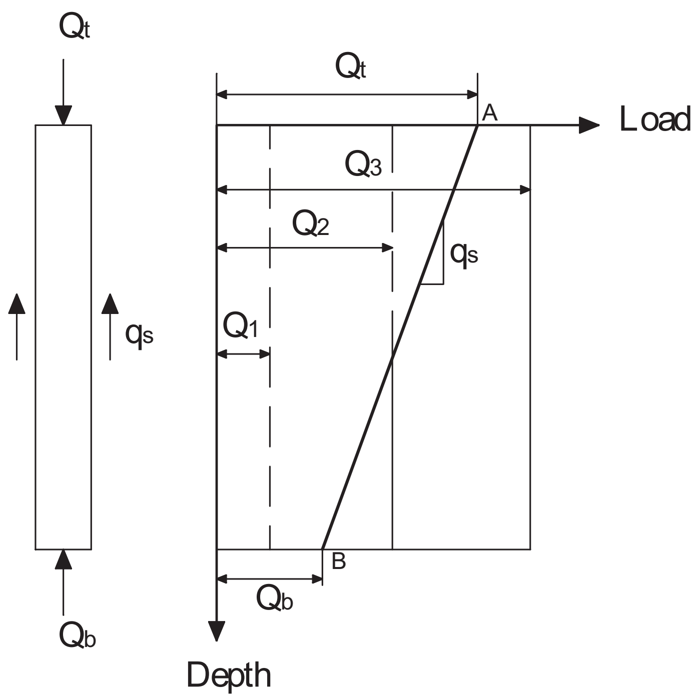


Figure 64. Effect definition of anomalies.

Anomalies affect the capacity of drilled shafts, only if the structural capacity of a shaft with anomaly is less than the axial load in the shaft at any depth where a anomaly is located. Figure 64 shows the distribution of the axial load along a drilled shaft. With the same anomaly at any depth, the structural capacity, Q_1 (or Q_3), is constant as represented by the vertical line in Figure 64. If the structural capacity line lies on the left side of the axial force line (no intersection), $Q_1 \leq Q_b$, the anomaly affects the drilled shaft capacity at any location; and the structural capacity controls. If the structural capacity line lies on the right side of the axial force line (no intersection), $Q_3 \geq Q_t$, the drilled shaft structure is much stronger than the geotechnical capacity; the anomaly has no affect on the shaft structural capacity at any location; and the geotechnical capacity controls. If the structural capacity line cuts the axial force line into two parts, $Q_b < Q_2 < Q_t$, anomalies located above the intersection point will have an effect on the drill shaft capacity; and the structural capacity controls. Anomalies located below the intersection point have no effect, and the geotechnical capacity controls instead. The capacity indicated by the intersection of point A of the shaft-load transfer curve with the horizontal coordinate as shown in Figure 64 gives the geotechnical capacity of a drilled shaft.

5.6 CAPACITIES OF DRILLED SHAFTS IN COHESIVE SOILS

Geotechnical capacities of drilled shafts in cohesive soils are calculated using the α method and also obtained from the load-settlement curve for the soft, medium, and stiff clays. The method was also used to obtain the geotech capacities for very stiff clay and extremely stiff clay, where the load is the total load applied to a drilled shaft, by the finite element analyses. In finite element analyses, the drilled shaft capacities are selected as the load at a point with maximum curvature on a load-settlement curve as shown in Figures 65 and 66. The results of the two methods are compared in Table 18. In finite element analysis, at the failure load, the side resistances are the same as those in the α method; the tip resistances from the finite element analysis are, however, higher. The values of N_c^* predicted from the finite element method are about 9 to 11 for drilled shafts of both 1-m and 2-m in diameter, which is somewhat higher than the values used in the computation of side shear resistance in conventional drilled shaft design (Reese, et al., 2006). These values of N_c^* and $\alpha = 1$ are used to compute the shaft-load transfer curves at failure load by using Equations. 1 and 6 shown in Figures 67, 68, 69, and 70 for both 1-m and 2-m in diameter of drilled shafts.

Table 18. Geotechnical capacity of drilled shafts in cohesive soil.

Diameter (m)	Capacity (kPa)	FEM			α method		
		c_u (kPa)			c_u (kPa)		
		25	50	100	25	50	100
1	Q_s (Shaft)	1,570.8	3,141.6	6,283.2	1,570.8	3,141.6	6,283.2
	Q_b (Base)	185.2	370.4	886.8	176.7	353.4	706.8
	Q_t (Total)	1,756.0	3,512.0	7,170.0	1,747.5	3,495.0	6,990.0
2	Q_s (Shaft)	3,141.6	6,283.2	12,566.4	3,141.6	6,283.2	12,566.4
	Q_b (Base)	857.6	1,725.8	3,450.6	706.8	1,413.7	2827.4
	Q_t (Total)	4,004.0	8,009.0	16,017.0	3,848.4	7,696.9	15,393.8

Table 18. (continued).

Diameter (m)	Capacity (kPa)	FEM		α method	
		c_u (kPa)		c_u (kPa)	
		200	300	200	300
1	Q_s (Shaft)	12,562	18,842	12,562	18,842
	Q_b (Base)	1,608	2,720	1,414	2,120
	Q_t (Total)	14,170	21,562	13,976	20,962
2	Q_s (Shaft)	25,148	37,685	25,148	37,685
	Q_b (Base)	5,655	8,519	5,655	8,482
	Q_t (Total)	30,803	46,205	30,803	4,6167

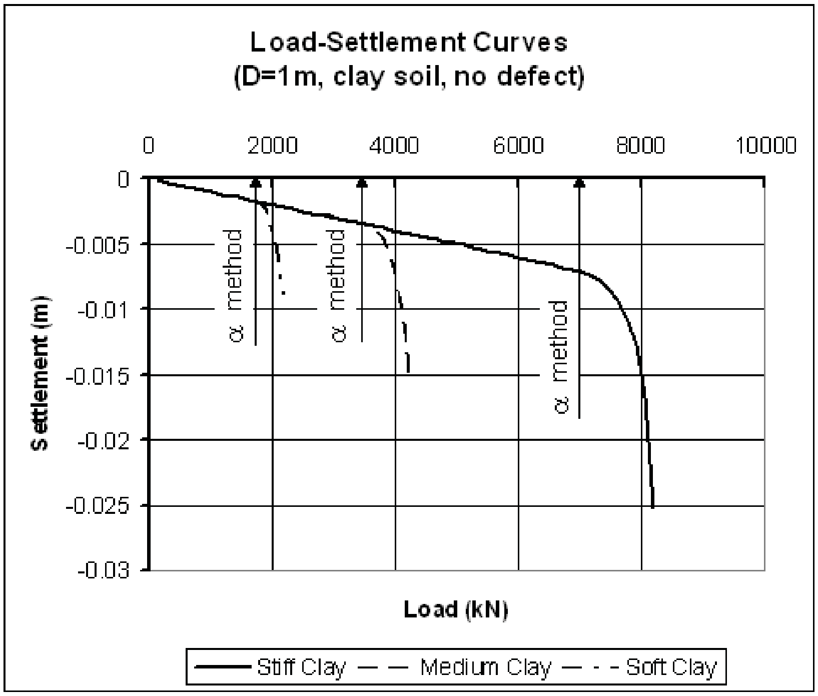


Figure 65. Load-settlement curves for 1-m diameter drilled shaft in clay with various stiffness.

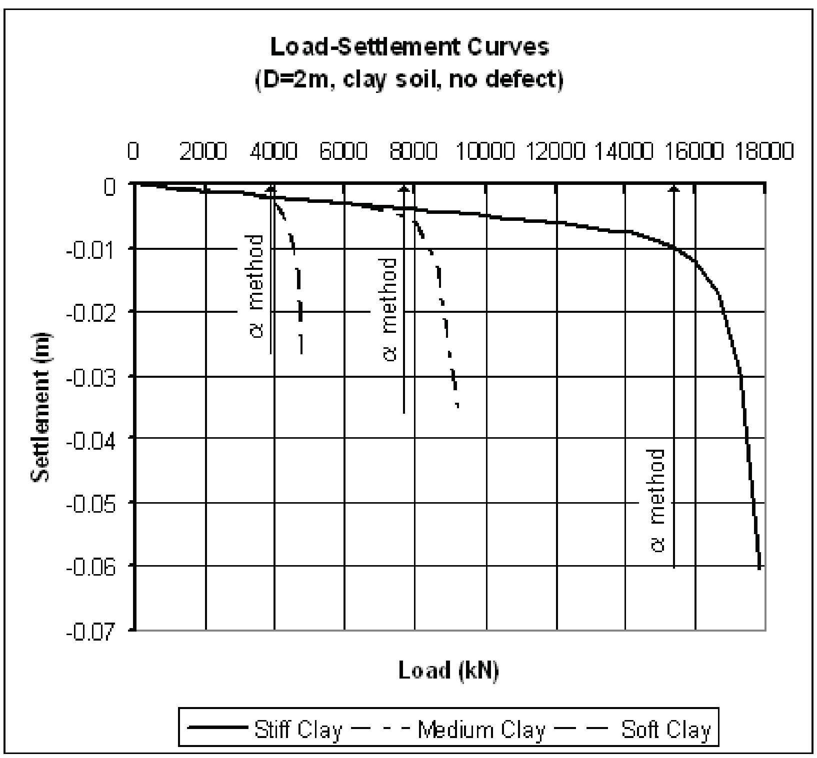


Figure 66. Load-settlement curves for 2-m diameter drilled shaft in clay with various stiffness.

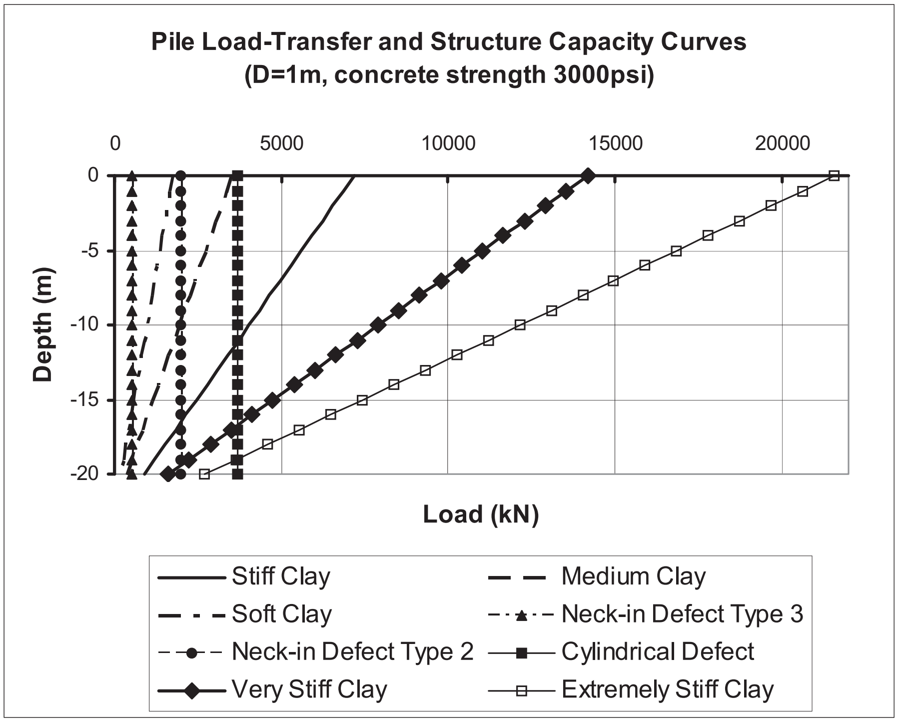


Figure 67. Shaft-load transfer and structural capacity curves for 1-m drilled shafts with 3,000 psi concrete constructed in clay.

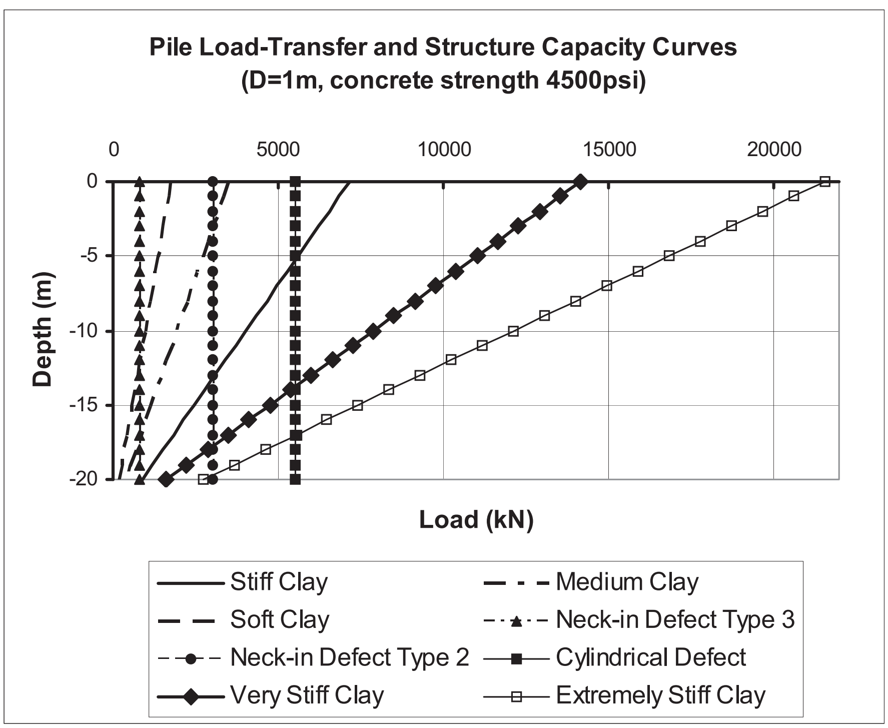


Figure 68. Shaft-load transfer and structural capacity curves for 1-m drilled shafts with 4,500 psi concrete constructed in clay.

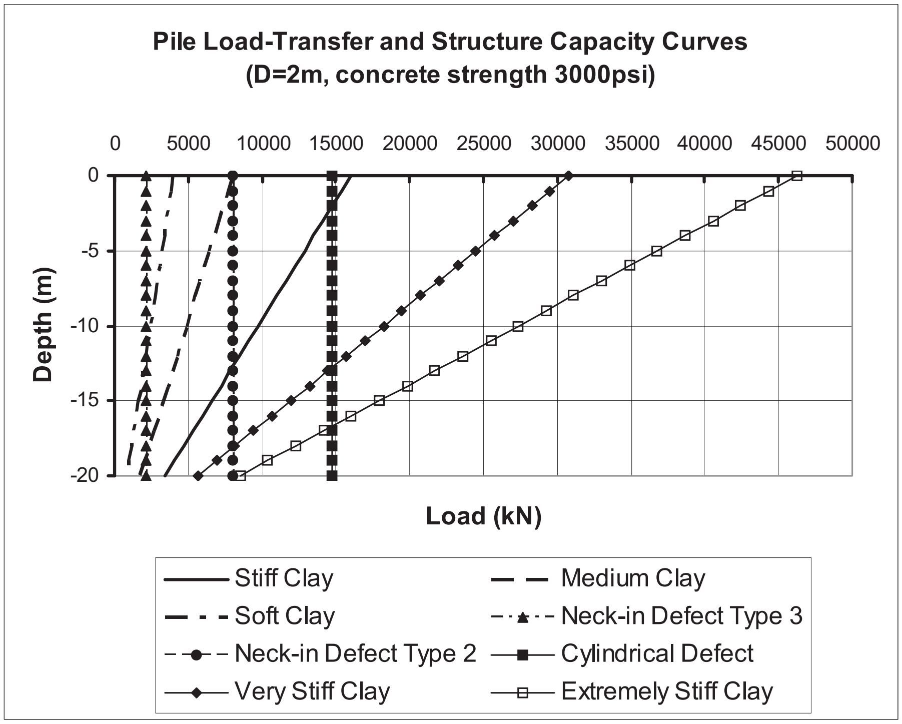


Figure 69. Shaft-load transfer and structural capacity curves for 2-m drilled shafts with 3,000 psi concrete constructed in clay.

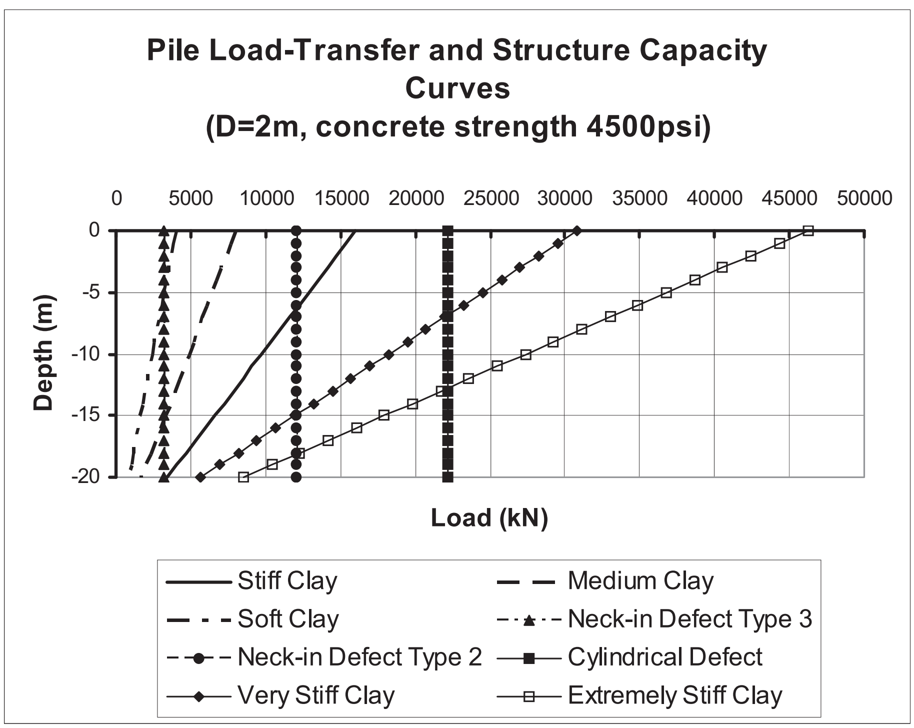


Figure 70. Shaft-load transfer and structural capacity curves for 2-m drilled shafts with 4,5000 psi concrete constructed in clay.

As shown in Figures 69 and 70, each point on a structural capacity gives not only the structural capacity but also the anomaly location. When the point on a structural capacity line lies above a shaft-load transfer curve, then it indicates that the structural capacity is smaller than the corresponding shaft load; and the anomaly is said to affect negatively the capacity of drilled shafts. In this case, the structural capacity controls capacity of drilled shafts. Thus, the capacity of drilled shafts with anomalies located above the intersecting point is equal to the structural capacity with anomalies. This structural capacity is then compared to the geotechnical capacity, and the smaller one then is the drilled shaft capacity. The structural capacity reduction is defined as the ratio of the capacity with anomalies to the capacity without anomalies. The capacities of drilled shafts with anomalies are shown in Tables 19 and 20 for drilled shafts of 1-m diameter and Tables 21 and 22 for drilled shafts of 2-m diameter.

The structural capacity of a drilled shaft with a cubical anomaly as shown in Table 16 is much higher than its corresponding geotechnical capacities of drilled shafts (Table 18), and this anomaly has no effect on drilled shaft capacity. The effect on capacity of drilled shafts of all other anomaly types with a higher reduction of cross-sectional areas depends on size, location of anomaly, anomaly concentricity, and soil strength as can be seen in Figures 67, 68, 69, and 70.

The drilled shaft capacity reduction in clay with 1- to 1.2-m anomaly length is shown in Table 19 to Table 22. The structural anomaly in drilled shafts of 3000 psi concrete strength has more effect than the anomaly in drilled shafts of 4500 psi concrete strength because the structural capacity with 3000 psi concrete strength is smaller than that with 4500 psi concrete strength. For 2-m diameter drilled shafts with 4500 psi concrete strength, only the type 3 neck-in anomaly reduced the drilled shaft capacity.

The effect of anomalies depends on the slope of load transfer curve (or the strength of clay soil), especially for deep anomalies. For a given anomaly, the geotechnical load transfer to soil increases as the soil strength increases and, thus, the effect of anomaly decreases. At the same applied load, anomaly sections of drilled shafts in soft clay experiences more load than in stiff clay. The large anomalies significantly reduce axial stiffness of drilled shafts before failure. The load-settlement curves of drilled shafts with anomalies are below the load-settlement curves of drilled shafts without anomalies (see the Figures in the Appendix).

In comparison of neck-in anomaly Type 1 and cylindrical anomaly with the same reduction of cross-sectional area, the capacities of drilled shafts with neck-in Type 1 anomaly is much higher than those of drilled shafts with cylindrical anomaly as shown in Figures 71 and 72. In all analyses, all anomaly voids are assumed to be empty, which seems appropriate when a very weak soil fills the anomaly voids around the exterior surface of a drilled shaft.

A nonconcentric anomaly has a higher effect on the drilled shaft capacity than a concentric anomaly. This is due to the eccentricity caused by the bending moment in the shaft segment with anomaly under an axial load. In drilled shafts with nonconcentric anomaly near the shaft top, the structural capacities are generally less than those of the shafts with cylindrical anomalies of the same cross-sectional area reduction. For anomalies at greater depth, such as the anomaly at the middle of the shaft, the soil surrounding the drilled shaft can fail, so that the structural capacity of a drilled shaft with a nonconcentric anomaly could be higher; therefore, the anomaly effect is of no significance. The capacity reductions are given in Tables 23 and 24.

The length of a anomaly, as defined earlier in Section 5.2, also has an affect on the capacity of a drilled shaft. For a long neck-in anomaly with no interface between soil and shaft, side resistance will be lost. The structural capacity of a anomaly segment is also affected by the length of the anomaly because of two end conditions. The longer anomaly has less capacity than the shorter anomaly as shown in Figure 73.

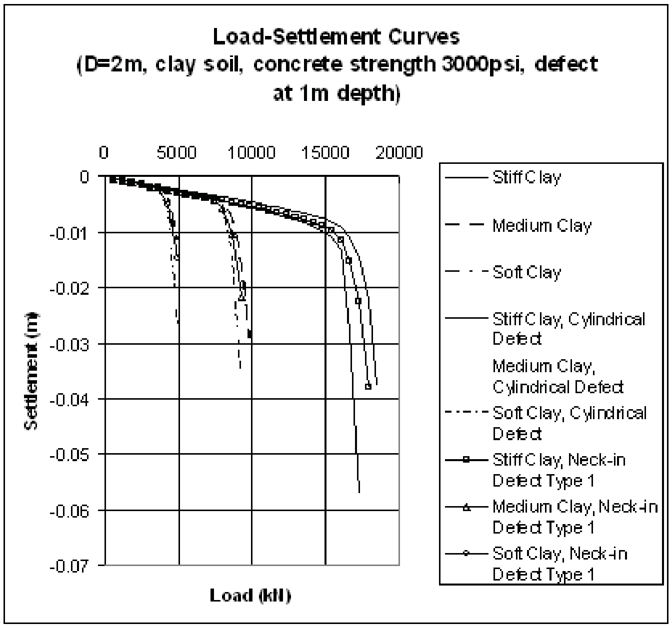


Figure 71. Neck-in anomaly Type 1 and cylindrical anomaly at 1-m depth, D = 2 m.

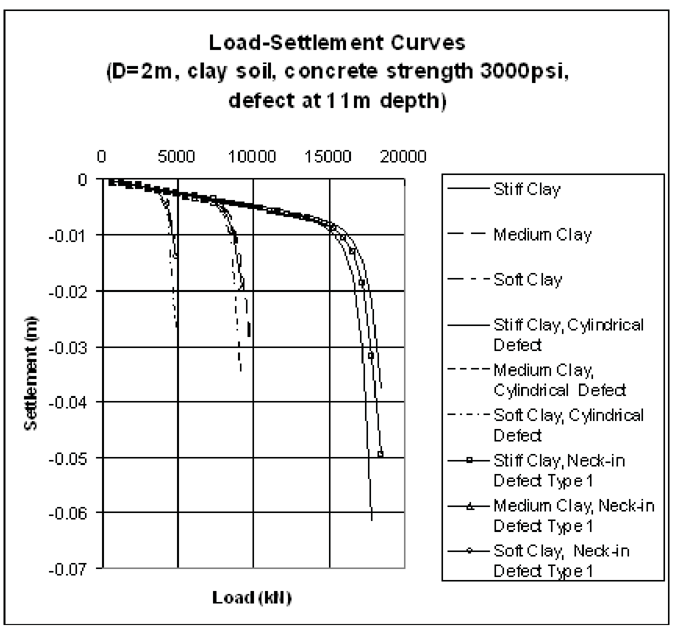


Figure 72. Neck-in anomaly Type 1 and cylindrical anomaly at 11-m depth, D = 2 m.

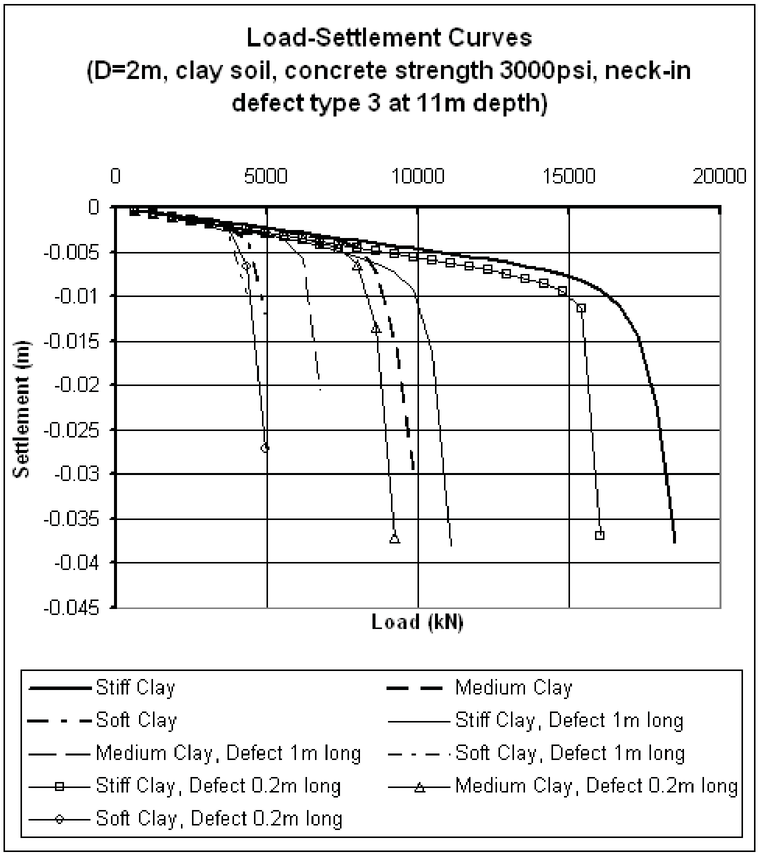


Figure 73. Comparison of short and long anomalies.

Table 19. Capacity reduction for the case of concrete strength 3,000 psi, shaft in clay, shaft diameter D = 1 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly type	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Cylindrical	Top	1,756	0
		Middle	1,756	0
		Bottom	1,756	0
	Neck-in type 2	Top	1,756	0
		Middle	1,756	0
		Bottom	1,756	0
	Neck-in type 3	Top	770	56.2
		Middle	1,540	12.3
		Bottom	1,756	0
50	Cylindrical	Top	3,512	0
		Middle	3,512	0
		Bottom	3,512	0
	Neck-in type 2	Top	2,156	38.6
		Middle	3,512	0
		Bottom	3,512	0
	Neck-in type 3	Top	770	78.0
		Middle	2,464	30
		Bottom	3,512	0
100	Cylindrical	Top	4,158	42.0
		Middle	7,170	0
		Bottom	7,170	0
	Neck-in type 2	Top	2,310	67.8
		Middle	6,006	16.2
		Bottom	7,170	0
	Neck-in type 3	Top	924	87.0
		Middle	4,312	41.2
		Bottom	6,930	3.3

Table 20. Capacity reduction for the case of concrete strength 4,500 psi, shaft in clay, shaft diameter D = 1 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly type	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Cylindrical	Top	1,756	0
		Middle	1,756	0
		Bottom	1,756	0
	Neck-in type 2	Top	1,756	0
		Middle	1,756	0
		Bottom	1,756	0
	Neck-in type 3	Top	770	56.0
		Middle	1,694	3.5
		Bottom	1,756	0
50	Cylindrical	Top	3,512	0
		Middle	3,512	0
		Bottom	3,512	0
	Neck-in type 2	Top	3,234	8.0
		Middle	3,512	0
		Bottom	3,512	0
	Neck-in type 3	Top	924	74.0
		Middle	2,772	21.0
		Bottom	3,512	0
100	Cylindrical	Top	5,852	18.0
		Middle	7,170	0
		Bottom	7,170	0
	Neck-in type 2	Top	3,388	53.0
		Middle	6,776	5.5
		Bottom	7,170	0
	Neck-in type 3	Top	1,078	85.0
		Middle	4,620	36.0
		Bottom	7,170	0

Table 21. Capacity reduction for the case of concrete strength 3,000 psi, shaft in clay, shaft diameter D = 2 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly type	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Cylindrical	Top	4,004	0
		Middle	4,004	0
		Bottom	4,004	0
	Neck-in type 2	Top	4,004	0
		Middle	4,004	0
		Bottom	4,004	0
	Neck-in type 3	Top	1,848	54.0
		Middle	4,004	0
		Bottom	4,004	0
50	Cylindrical	Top	8,009	0
		Middle	8,009	0
		Bottom	8,009	0
	Neck-in type 2	Top	8,009	0
		Middle	8,009	0
		Bottom	8,009	0
	Neck-in type 3	Top	2,464	69.0
		Middle	6,160	23.0
		Bottom	8,009	0
100	Cylindrical	Top	16,017	0
		Middle	16,017	0
		Bottom	16,017	0
	Neck-in type 2	Top	10,473	34.6
		Middle	15,402	3.8
		Bottom	16,017	0
	Neck-in type 3	Top	2,464	84.6
		Middle	9,857	38.5
		Bottom	14,785	7.7

Table 22. Capacity reduction for the case of concrete strength 4,500 psi, shaft in clay, shaft diameter D = 2 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly type	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Cylindrical	Top	4,004	0
		Middle	4,004	0
		Bottom	4,004	0
	Neck-in type 2	Top	4,004	0
		Middle	4,004	0
		Bottom	4,004	0
	Neck-in type 3	Top	3,080	30.00
		Middle	4,004	0
		Bottom	4,004	0
50	Cylindrical	Top	8,009	0
		Middle	8,009	0
		Bottom	8,009	0
	Neck-in type 2	Top	8,009	0
		Middle	8,009	0
		Bottom	8,009	0
	Neck-in type 3	Top	3,696	54.00
		Middle	6,776	15.04
		Bottom	8,009	0
100	Cylindrical	Top	16,017	0
		Middle	16,017	0
		Bottom	16,017	0
	Neck-in type 2	Top	15,401	3.08
		Middle	16,017	0
		Bottom	16,017	0
	Neck-in type 3	Top	3,696	76.09
		Middle	11,089	30.76
		Bottom	16,017	0

Table 23. Capacity reduction for nonconcentric anomaly, concrete strength 3,000 psi, shaft in clay, diameter D = 2 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Top	4,004	0
	Middle	4,004	0
	Bottom	4,004	0
50	Top	6,160	23.0
	Middle	8,009	0
	Bottom	8,009	0
100	Top	6,160	61.5
	Middle	16,017	0
	Bottom	16,017	0

Table 24. Capacity reduction for nonconcentric anomaly, concrete strength 4,500 psi, shaft in clay, diameter D = 2 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Top	4,004	0
	Middle	4,004	0
	Bottom	4,004	0
50	Top	6,160	23.0
	Middle	8,009	0
	Bottom	8,009	0
100	Top	6,160	61.5
	Middle	16,017	0
	Bottom	16,017	0

5.7 CAPACITIES OF DRILLED SHAFTS IN COHESIONLESS SOILS

In the case of drilled shafts in sandy soils, the soil capacities can be determined by following the procedures outlined in the FHWA manual (O'Neill and Reese, 1999) and by utilizing the finite element analyses. For drilled shafts in contractive loose sand, the capacity is computed at the point with maximum curvature on load-settlement as shown in (Figures 74 and 75). For the drilled shaft in medium and dense sands, the load-settlement curves in finite element analyses do not show a significant maximum curvature because of high dilation. Hence, the capacities computed by finite element analyses are based on the maximum stress at the shaft base as represented in Eq. 13 as outlined in the FHWA manual (O'Neill and Reese, 1999) (N_{SPT} = 50 for dense sand and N_{SPT} = 30 for medium sand). The analysis results are shown in Table 25. The shaft-load transfer curves and the structural capacity lines for drilled shafts with different anomalies are summarized in Figures 76 - 79. Tables 26 - 31 give the drilled shaft capacity reductions for the drilled shafts with different anomalies, where drilled shaft capacities are the smaller of structural and geotechnical capacities.

Table 25. Capacities of drilled shafts in sandy soils.

Diameter (m)	Capacity (kPa)	FEM			FHWA (1999) method		
		Friction Angle (φ)			Friction Angle (φ)		
		30^0	40^0	45^0	30^0	40^0	45^0
1	Q_s (Shaft)	3737	4905	8324	-	7923	7923
	Q_b (Base)	1037	1405	2107	-	1354	2258
	Q_t (Total)	4774	6310	10431	-	9278	10181
2	Q_s (Shaft)	7117	13587	17406	-	15847	15847
	Q_b (Base)	3356	5290	8798	-	5419	9032
	Q_t (Total)	10473	18877	26204	-	21266	24879

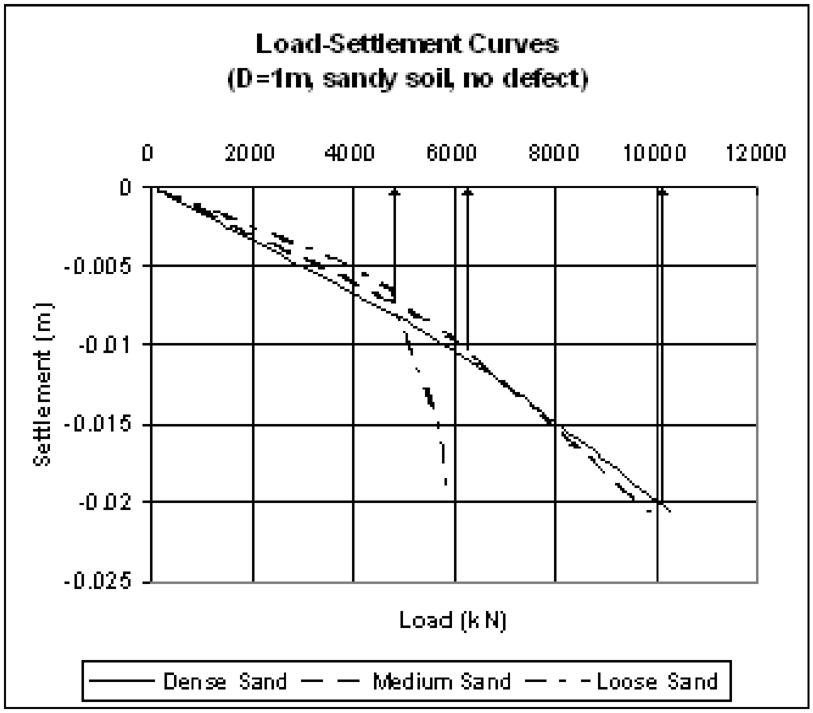


Figure 74. Load-settlement curves for drilled shafts of 1-m diameter in sand.

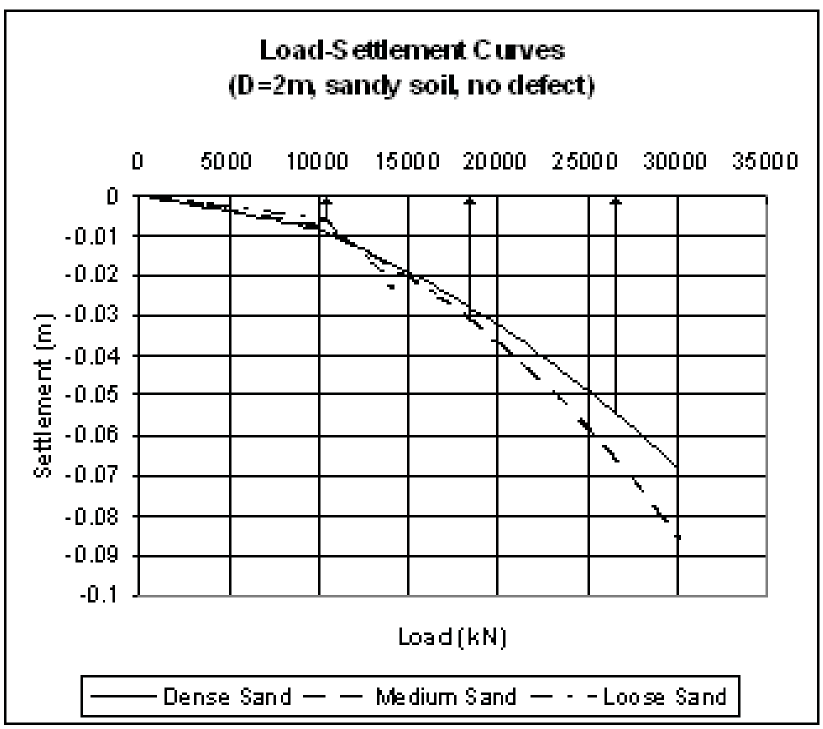


Figure 75. Load-settlement curves for drilled shafts of 2-m diameter in sand.

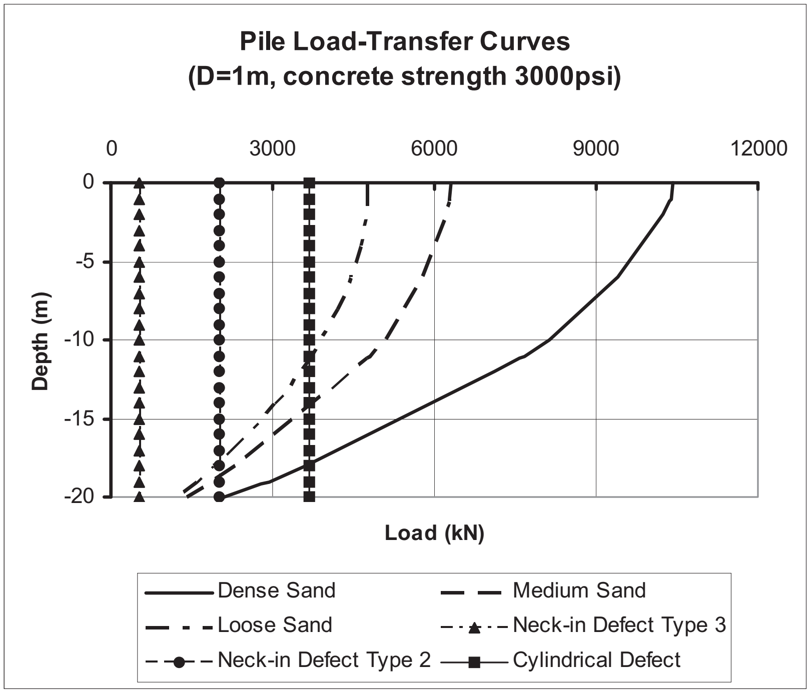


Figure 76. Shaft-load transfer curves for drilled shafts of 1-m diameter in sand.

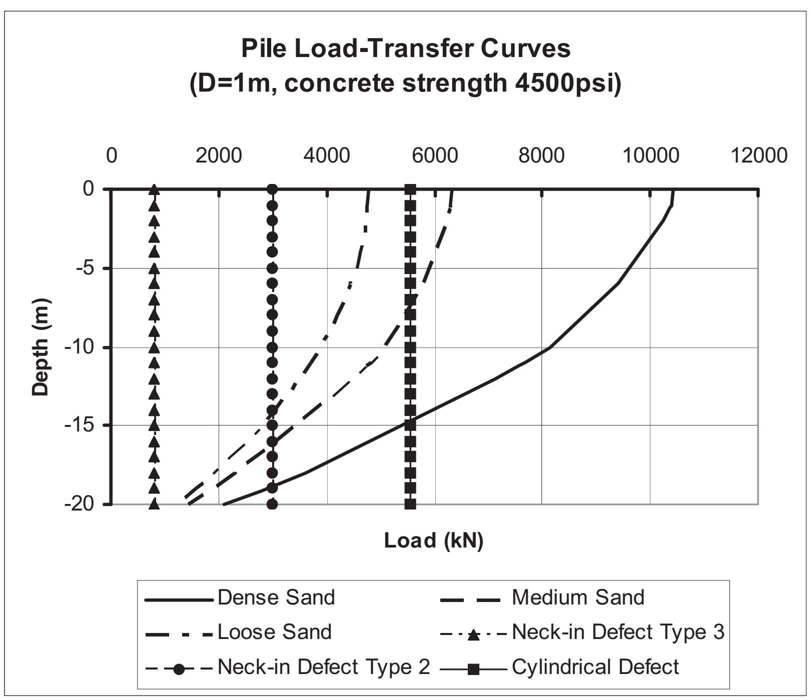


Figure 77. Shaft-load transfer curves for drilled shafts of 1-m diameter in sand.

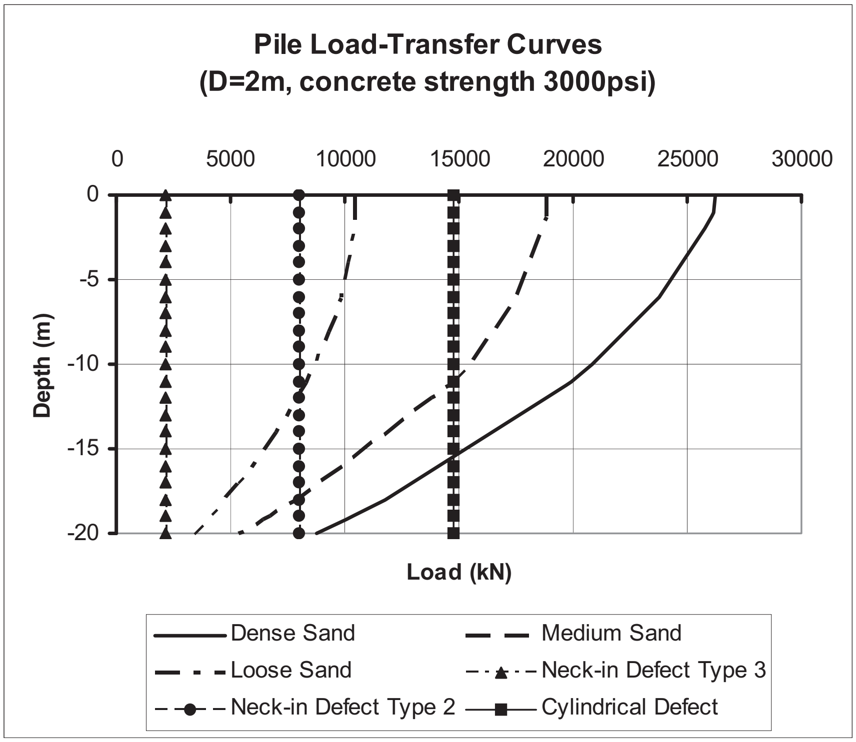


Figure 78. Shaft-load transfer curves for drilled shafts of 2-m diameter in sand.

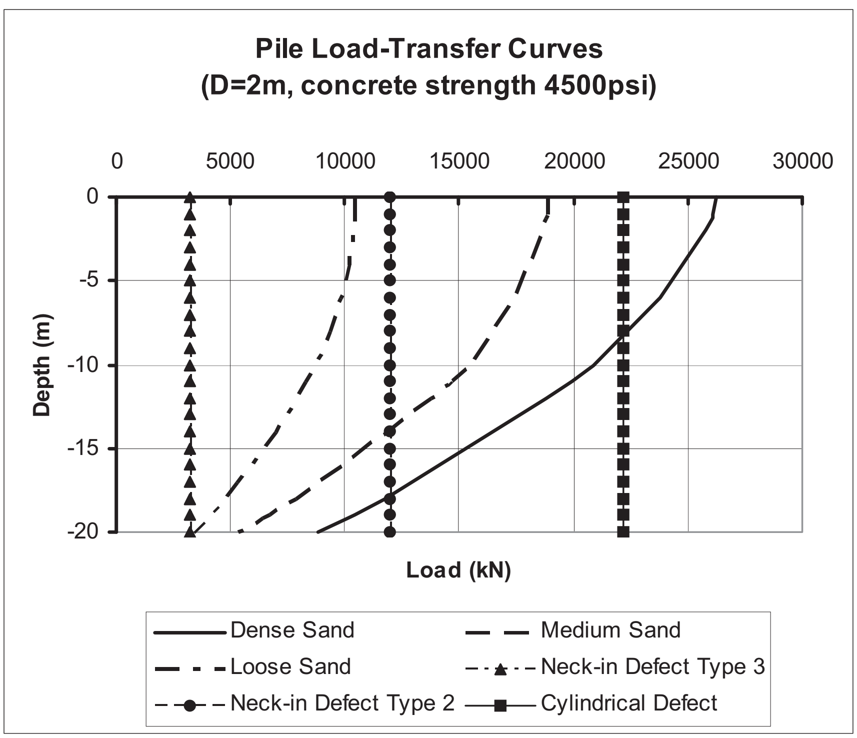


Figure 79. Shaft-load transfer curves for drilled shafts of 2-m diameter in sand.

Table 26. Drilled shaft capacity reduction for the case of concrete strength 3,000 psi, shaft in sand, shaft diameter D = 1 m, anomaly length 1-1.2 m.

Friction angle, φ	Anomaly type	Anomaly location	Capacity (kN)	Capacity reduction (%)
30	Cylindrical	Top	3,850	19.4
		Middle	4,774	0
		Bottom	4,774	0
	Neck-in type 2	Top	2,002	58.0
		Middle	3,234	32.2
		Bottom	4,774	0
	Neck-in type 3	Top	462	90.3
		Middle	1,694	64.5
		Bottom	4,158	12.9
40	Cylindrical	Top	3,850	39.0
		Middle	5,544	12.1
		Bottom	6,310	0
	Neck-in type 2	Top	2,002	68.3
		Middle	3,542	43.9
		Bottom	6,310	0
	Neck-in type 3	Top	462	92.7
		Middle	1,848	70.7
		Bottom	4,620	27.0
45	Cylindrical	Top	3,850	63.0
		Middle	5,698	45.4
		Bottom	10,431	0
	Neck-in type 2	Top	2,002	80.8
		Middle	3,696	64.6
		Bottom	10,431	0
	Neck-in type 3	Top	462	95.6
		Middle	2,156	79.3
		Bottom	4,158	60.0

Table 27. Drilled shaft capacity reduction for the case of concrete strength 4,500 psi, shaft in sand, shaft diameter D = 1 m, anomaly length 1-1.2 m.

Friction angle, φ	Anomaly type	Anomaly location	Capacity (kN)	Capacity reduction (%)
30	Cylindrical	Top	4,774	0
		Middle	4,774	0
		Bottom	4,774	0
	Neck-in type 2	Top	2,926	38.70
		Middle	4,312	9.70
		Bottom	4,774	0
	Neck-in type 3	Top	770	83.90
		Middle	1,848	61.30
		Bottom	4,158	12.90
40	Cylindrical	Top	4,928	21.90
		Middle	6,310	0
		Bottom	6,310	0
	Neck-in type 2	Top	3,080	51.20
		Middle	4,774	24.34
		Bottom	6,310	0
	Neck-in type 3	Top	770	87.80
		Middle	2,310	63.40
		Bottom	4,620	27.00
45	Cylindrical	Top	4,928	58.80
		Middle	8,808	15.60
		Bottom	10,431	0
	Neck-in type 2	Top	3,080	70.40
		Middle	4,928	52.70
		Bottom	10,431	0
	Neck-in type 3	Top	770	92.60
		Middle	2,464	76.40
		Bottom	4,620	55.70

Table 28. Drilled shaft capacity reduction for the case of concrete strength 3,000 psi, shaft in sand, shaft diameter D = 2 m, anomaly length 1-1.2 m.

Friction angle, φ	Anomaly type	Anomaly location	Capacity (kN)	Capacity reduction (%)
30	Cylindrical	Top	10,473	0
		Middle	10,473	0
		Bottom	10,473	0
	Neck-in type 2	Top	9,857	5.9
		Middle	10,473	0
		Bottom	10,473	0
	Neck-in type 3	Top	1,848	82.3
		Middle	4,312	58.8
		Bottom	9,857	5.9
40	Cylindrical	Top	15,401	18.4
		Middle	18,877	0
		Bottom	18,877	0
	Neck-in type 2	Top	9,857	47.8
		Middle	12,937	31.5
		Bottom	18,877	0
	Neck-in type 3	Top	1,848	90.2
		Middle	5,544	70.6
		Bottom	10,473	44.5
45	Cylindrical	Top	15,401	41.2
		Middle	20,946	20.0
		Bottom	26,204	0
	Neck-in type 2	Top	9,857	62.4
		Middle	13,553	48.3
		Bottom	26,204	0
	Neck-in type 3	Top	1,848	92.9
		Middle	5,544	78.8
		Bottom	10,473	60.0

Table 29. Drilled shaft capacity reduction for the case of concrete strength 4,500 psi, shaft in sand, shaft diameter D = 2 m, anomaly length 1-1.2 m.

Friction angle, φ	Anomaly type	Anomaly location	Capacity (kN)	Capacity reduction (%)
30	Cylindrical	Top	10,473	0
		Middle	10,473	0
		Bottom	10,473	0
	Neck-in type 2	Top	10,473	0
		Middle	10,473	0
		Bottom	10,473	0
	Neck-in type 3	Top	3,080	70.6
		Middle	5,544	47.0
		Bottom	9,857	5.9
40	Cylindrical	Top	18,877	0
		Middle	18,877	0
		Bottom	18,877	0
	Neck-in type 2	Top	14,785	21.7
		Middle	17,250	8.6
		Bottom	18,877	0
	Neck-in type 3	Top	3,080	83.7
		Middle	6,160	67.4
		Bottom	11,705	38.0
45	Cylindrical	Top	20,946	20.0
		Middle	26,204	0
		Bottom	26,204	0
	Neck-in type 2	Top	14,785	43.6
		Middle	17,250	34.2
		Bottom	26,204	0
	Neck-in type 3	Top	3,080	88.2
		Middle	6,160	76.5
		Bottom	12,937	50.6

Table 30. Drilled shaft capacity reduction for nonconcentric anomaly, concrete strength 3,000 psi, soil in sand, diameter D = 2 m, anomaly length 1-1.2 m.

Friction angle, φ	Anomaly location	Capacity (kN)	Capacity reduction (%)
30	Top	6,160	41.0
	Middle	10,473	0
	Bottom	10,473	0
40	Top	6,160	67.4
	Middle	18,877	0
	Bottom	18,877	0
45	Top	6,160	76.5
	Middle	26,204	0
	Bottom	26,204	0

Table 31. Drilled shaft capacity reduction for nonconcentric anomaly, concrete strength 4,500 psi, diameter D = 2m, soil in sand, anomaly length 1-1.2m.

Friction angle, φ	Anomaly location	Capacity (kN)	Capacity reduction (%)
30	Top	6,160	41.0
	Middle	10,473	0
	Bottom	10,473	0
40	Top	6,160	67.4
	Middle	18,877	0
	Bottom	18,877	0
45	Top	6,160	76.5
	Middle	26,204	0
	Bottom	26,204	0

5.8 Capacities of drilled shafts in cohesive soil with bedrock at shaft tip

For the drilled shafts with cubical anomalies, the drilled shaft is in clay soil with the shaft tip on rock, and the drilled shaft capacity is equal to the structural capacity. The reductions of capacities are given in Table 32 to Table 35. As observed in other cases, the anomalies of the drilled shafts in soft clay impose more significant effect on drilled shaft capacity than the anomalies in drilled shafts in stiff clay.

Table 32. Drilled shaft capacity reduction for the case of concrete strength 3,000 psi, shaft in clay with bedrock at shaft tip, shaft diameter D = 1 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Top	16,200	18.72
	Middle	16,900	15.21
	Bottom	17,500	12.20
50	Top	16,300	18.22
	Middle	17,700	11.19
	Bottom	18,900	5.17
100	Top	16,500	17.21
	Middle	19,300	3.17
	Bottom	19,931	0.00
200	Top	16,800	15.71
	Middle	19,931	0.00
	Bottom	19,931	0.00
300	Top	17,100	14.20
	Middle	19,931	0.00
	Bottom	19,931	0.00

Table 33. Drilled shaft capacity reduction for the case of concrete strength 4,500 psi, shaft in clay with bedrock at shaft tip, shaft diameter D = 1 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Top	21,000	21.37
	Middle	21,700	18.75
	Bottom	22,400	16.13
50	Top	21,100	21.00
	Middle	22,500	15.76
	Bottom	23,800	10.89
100	Top	21,300	20.25
	Middle	24,100	9.76
	Bottom	26,708	0.00
200	Top	21,700	18.75
	Middle	26,708	0.00
	Bottom	26,708	0.00
300	Top	22,100	17.25
	Middle	26,708	0.00
	Bottom	26,708	0.00

Table 34. Drilled shaft capacity reduction for the case of concrete strength 3,000 psi, shaft in clay with bedrock at shaft tip, shaft diameter D = 2 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Top	65,000	18.97
	Middle	66,600	16.97
	Bottom	67,700	15.60
50	Top	65,200	18.72
	Middle	68,300	14.85
	Bottom	70,600	11.99
100	Top	65,600	18.22
	Middle	71,900	10.36
	Bottom	76,300	4.88
200	Top	66,300	17.35
	Middle	78,900	1.64
	Bottom	80,214	0.00
300	Top	66,900	16.60
	Middle	80,214	0.00
	Bottom	80,214	0.00

Table 35. Capacity reduction for the case of concrete strength 4,500 psi, shaft in clay with bedrock at shaft tip, shaft diameter D = 2 m, anomaly length 1-1.2 m.

Cohesion, C_u (kPa)	Anomaly location	Capacity (kN)	Capacity reduction (%)
25	Top	84,400	21.35
	Middle	86,000	19.86
	Bottom	87,100	18.84
50	Top	84,600	21.17
	Middle	87,800	18.18
	Bottom	90,000	16.13
100	Top	85,000	20.79
	Middle	91,300	14.92
	Bottom	95,700	10.82
200	Top	85,800	20.05
	Middle	98,300	8.40
	Bottom	107,313	0.00
300	Top	86,400	19.49
	Middle	105,400	1.78
	Bottom	107,313	0.00