Estimating Downdrag Forces in Piles
and Means of Minimizing or Eliminating Downdrag

By William Enkeboll

PILES installed in an area of subsidence may be subjected to downdrag forces, often referred to as negative skin friction. When the soil strata alongside a pile decrease in height with respect to the pile, downdrag forces develop. Usually a decrease in height of the soil strata is caused by the weight of fill placed over a deposit of compressible soil, but it may be caused by consolidation of compressible soil under its own weight, if it is not fully consolidated, or by desiccation. Only downdrag associated with subsidence due to the weight of fill is considered in this article. In the event subsidence occurs due to consolidation of the soil beneath the pile tips and the soil strata alongside the piles do not decrease in height, downdrag forces will not be developed in the piles.

Downdrag results from the downward movement, or the tendency to downward movement, with respect to a pile, of the soil surrounding the pile. The magnitude of the downdrag force is limited by the shear strength of the soil adjacent to the pile or the frictional resistance which may be developed between the soil and the pile. It is appropriate to designate the downdrag evaluated on the basis of the shear strength and frictional resistance as the "potential" downdrag, since it may not be completely developed. If the weight of fill adjacent to a pile is sufficiently small, the downdrag force actually developed will be less than the potential downdrag.

Estimating Downdrag Forces

The following example illustrates a method of estimating downdrag forces. The soil profile, shown in Figure 1, was obtained from a foundation investigation and is representative of soil conditions which lead to downdrag forces. The pertinent soil properties also are presented in Figure 1. In this case, eight feet of

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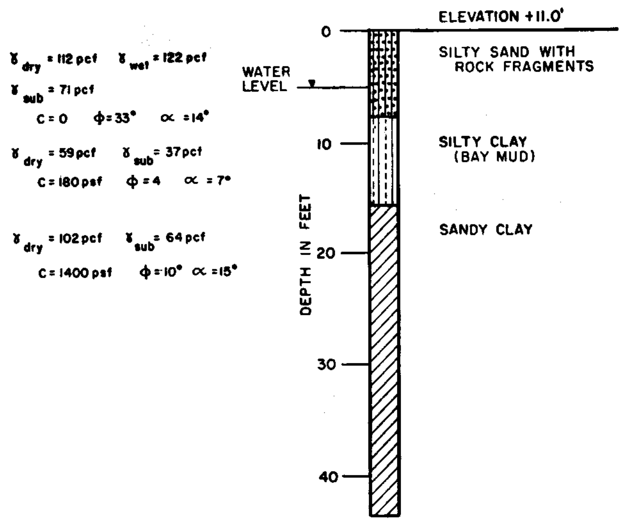
In 1947 he joined the firm of Dames & Moore, Consultants in Applied Earth Sciences. He became a partner in the firm in 1951 and was in charge of the Seattle office from its inception in 1947 to 1959 when he was transferred to take charge of the firm's San Francisco office. Much of Mr. Enkeboll's work in a wide variety of projects has involved the use of piling.

He is a Fellow in the American Society of Civil Engineers, Member of the Structural Engineers Association of Northern California, Member of the Consulting Engineers of California, as well as the San Francisco Engineers Club. Besides having served as President of the Seattle Section of the ASCE in 1957, he was a founding member of the Consulting Engineers Association of Washington, serving as its first Treasurer. He was secretary of the Structural Engineers Association of Northern California in 1964.



LOG OF BORING AND SOIL DATA

FIGURE 1

fill were placed to raise the grade to the desired elevation. The water level after filling was at a depth of five feet. It was necessary to support the material processing structures located in the filled area on piles because of the weak and compressible silty clay soils (bay mud) immediately underlying the fill. The sandy clay soils underlying the silty clay soils were stiff and capable of providing adequate support for piles. The weight of the fill caused consolidation to occur in the weak and compressible silty clay soils resulting in downdrag forces being developed.

The procedure used in estimating both downdrag forces and support is shown in Table 1. The calculations for support are included for the sake of completeness. The procedure followed is that presented in Reference 1. This procedure was developed by William W. Moore and Trent R. Dames.

The soil profile is divided into a convenient number of increments of depth, the fill being divided at the water level into two increments, the silty clay in two 4-ft. increments, and the sandy clay into three 10-ft. increments. The overburden pressure is calculated at the midpoint of each increment from the wet unit weight, δ_{wet}, of the soil above the water level and the submerged unit weight, δ_{sub}, of the soil below the water level. The shear strength is calculated at the midpoint of each increment using the customary expression for shear strength,

$$s = c + p \tan \phi,$$

where "s" is the shear strength, "c" is the cohesion, "p" is the normal pressure, and "ϕ" is the friction angle of the soil. The values of "c" and "ϕ" are based on the ultimate strength of the soil for downdrag and on the yield strength for support, and the overburden pressure is used for "p," the normal pressure.

In addition to the shear strength, the friction between the pile and the soil is considered. The friction is obtained by multiplying the tangent of the angle of friction between the soil and the pile, tan α, by the lateral pressure on the pile. The lateral pressure on the pile is greater than the overburden pressure when the pile is driven as a displacement pile. The lateral pres-

DEPTH BELOW GROUND SURFACE IN FT.	AVERAGE DEPTH BELOW GROUND SURFACE IN FT.	OVERBURDEN PRESSURE KIPS/SQ.FT.	AVERAGE SHEAR STRENGTH KIPS/SQ.FT.	LATERAL PRESSURE FACTOR $\frac{\pi S+P}{P}$	LATERAL PRESSURE FOR FRICTION KIPS/SQ.FT.	AVERAGE FRICTION KIPS/SQ.FT.	END BEARING IN KIPS	LATERAL AREA IN SQ.FT.				DOWNDRAG AND SUPPORT				
								PENETRATION IN FEET				PENETRATION IN FEET				
								16	26	36	46	16	26	36	46	
0																
	2½	.305	.198	3.04	.927	.231	—	12.24	13.54	14.85	16.17	2.43	2.69	2.94	3.20	
5																
	6½	.717	.465	3.04	2.178	.543	—	7.03	7.82	8.60	9.38	3.27	3.66	4.00	4.35	
8																
	10	.897	.243	1.84	1.651	.203	—	9.00	10.05	11.10	12.15	1.83	2.04	2.25	2.46	
12																
	14	1.045	.253	1.76	1.840	.226	1.76	8.59	9.64	10.69	11.73	1.94	2.17	2.41	2.65	
16																
	21	1.439	1.654	—	6.639	1.780	1.88	—	22.25	24.87	27.49	9.47	10.56	11.60	12.66	DOWNDRAG
													36.7	41.0	45.5	
26																
	31	2.079	1.767	—	7.629	2.055	2.01	—	—	22.25	24.87	—	—	39.8	44.0	
36																
	41	2.719	1.880	—	8.619	2.310	2.12	—	—	—	22.25	—	—		41.6	
46																
												1.76	38.58	82.81	133.22	SUPPORT FS = 1
												1.17	25.7	55.1	88.9	SUPPORT FS = 1.5

COMPUTATION FOR DOWNDRAG AND SUPPORT

Table 1

sure is equal to the overburden pressure multiplied by a lateral pressure factor. A simple expression for evaluating a lateral pressure factor is $\frac{\pi s + p}{p}$. Lateral pressure factors evaluated by means of this expression have been used successfully in predicting the supporting capacities of piles, and it is believed to be within reasonable limits of accuracy to use the same expression to estimate downdrag forces. It will be noted that in multiplying this expression for the lateral pressure factor into the overburden pressure, the lateral pressure is equal to $\pi s + p$. Thus, the lateral pressure could be obtained directly from the expression $\pi s + p$, but it is helpful to know the value of the lateral pressure factor. The procedure also lends itself to the use of lateral pressure factors evaluated by other means, if it should be desired to do so.

The end bearing does not affect the downdrag, but to complete the calculation for the supporting capacity, the end bearing has been conservatively estimated using the expression πsA where "A" is the end area of the pile.

The lateral area of the pile is computed for each increment for different pile penetrations. Each penetration coincides with a whole increment.

The shear strength or the friction, whichever is the smaller, is multiplied by the lateral area for each increment to obtain the downdrag or support for that increment. The smaller of the two values is underlined in the table.

The total downdrag is obtained by the summation of the downdrag per increment above the supporting soil stratum, and the total support is obtained by summation of the supporting forces.

The strains in the soil adjacent to the pile are large enough so that the ultimate shear strength of the soil or ultimate friction between the soil and the pile should be used without applying a factor of safety in calculating downdrag forces. This is analogous to calculating the forces which would be developed at failure. In contrast, the design supporting capacity is calculated with an appropriate factor of safety. In the example, a factor of safety of 1.5 has been used in arriving at the design supporting capacity.

The lateral area of a wood pile in the soils above the supporting soil increases as the penetration of the pile is increased because of the taper of the pile. It has been considered that the taper of the pile of the example has a taper of one inch in ten feet on the diameter. Thus, the downdrag increases with increasing penetration of the pile. For small differences in penetration, the change in downdrag is small. The variation is illustrated in Figure 2. The design supporting capacity of the soil on the pile is also plotted in Figure 2. *The units have been changed from kips in the calculations to tons in Figure 2.*

The required penetration into the supporting soil for a pile carrying a design load of 30 tons is 22 feet, if there were no downdrag. At a penetration of 22 feet

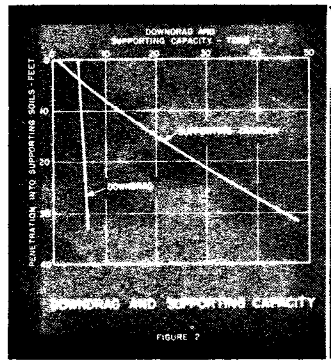
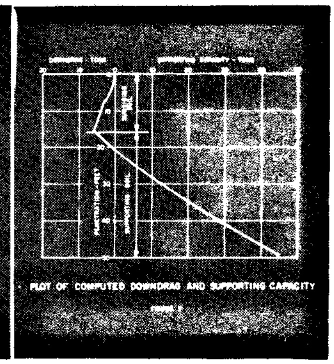


FIGURE 2



into the supporting soil, the downdrag is approximately 6 tons. Adding the downdrag load to the design load gives a total of 36 tons which must be resisted in the supporting soil. The required penetration for a load of 36 tons is 26 feet. This additional penetration of four feet to resist the downdrag results in a slight increase in the downdrag because of the greater surface area of the pile in the subsiding soil. The increase is not large enough to warrant increasing the pile penetration to provide additional support to resist it.

A convenient type of graph, from which the penetration into the supporting soil for a given load with downdrag already allowed for, is shown in Figure 3. In preparing such a graph, the variation in the downdrag with the pile penetration for tapered piles results in a small inaccuracy. If the downdrag is based on the probable maximum penetration, the degree of conservatism is very small and within the limits of accuracy of the calculations.

The downdrag on an interior pile in a large group of piles cannot exceed the weight of fill between the pile and half the distance to the adjacent piles. A pile spacing of 3 feet in both directions for a square pile pattern gives a weight of fill per pile, not allowing for the weight of fill displaced by the pile, of 3.7 tons using the unit weight of fill in the example. The weight of fill displaced by the pile is 0.25 tons. Normally, this is not deducted, since it is a small part of the total and it is within the limits of accuracy to ignore it.

Measurement of Downdrag

Downdrag forces may be much greater than in the example. The potential downdrag increases with the depth to the supporting stratum and the depth of fill.

It is not possible to allow properly for downdrag by use of a dynamic pile driving formula. At best, dynamic pile driving formulas are very approximate, and it appears impossible to develop a rational means of estimating downdrag from blow count data.

Downdrag may be measured by performing a load test by pulling a pile which has been driven to, or just short of, the supporting stratum. The total force required to withdraw the pile would give the potential downdrag load on the pile.

Methods to Reduce Downdrag

Downdrag forces may be reduced by predrilling in order to decrease the lateral pressures which develop through the soil displacement. Normally, it is desired that the soil provide lateral support to the pile. Therefore, a predrilled hole for the pile should be smaller than the diameter of the pile. If the hole will remain open after drilling until the pile is placed in it, it is normally drilled as a "dry" hole. If the hole caves, a mud slurry may be left in the hole to minimize caving. Even if caving does occur, some benefit is derived from the predrilling because of the soil removed.

The degree of accuracy with which it is possible to estimate downdrag forces when using the predrilling method is limited. In the example, the lateral pressure factor is approximately three in the fill and approximately one and three-fourths in the bay mud without predrilling. It is probable that the lateral pressure ratio would not be reduced below one and one-half by predrilling. Using a lateral pressure factor of one and one-half in both the fill and the bay mud gives the results shown in Table 2. The reduction in lateral pressure results in friction rather than shear strength being lower in the fill.

Downdrag forces may be reduced appreciably or eliminated by installing a steel shell (or other suitable type of shell) around the pile. The soil within the shell is removed and where a pile is laterally loaded, the space between the pile and shell is filled with sand. If a shell extends into the supporting soil stratum sufficiently far to resist the downdrag forces on it, it will not settle with respect to the pile. In this case, no downdrag forces would be transmitted to the pile. A shell which does not extend to the supporting soil stratum will settle with respect to the pile, resulting in some downdrag being transmitted to the pile through the sand between the pile and the shell.

The downdrag force from the sand between the pile and a settling shell may be approximated by considering the effect of arching in the sand between the pile and the shell. An expression developed in Reference 2 may be used in calculating the lateral pressure the sand exerts on the pile. Considering the lateral stress equal to the vertical stress in the sand, using the angle of friction between the sand and the pile in place of the friction angle in the sand, and recognizing the depth is large compared to the width of the space between the pile and the shell gives the expression

$$p_l = \frac{B\ \delta}{\tan\ \alpha}$$

where "p_l" is the lateral pressure, "B" is one-half the width of the space between the pile and the shell, "δ" is the unit weight of the sand (wet unit weight above the water table and submerged unit weight below), and "α" is the friction angle between sand and pile.

For a space of 6 inches between the pile and the shell and using, for the sand, a wet unit weight of 120 pounds per cubic foot, a submerged unit weight of 65 pounds per cubic foot, and a frictional angle "α" of 14° gives the results presented in Table 3.

Comparing the results of the computations for downdrag in Tables 1, 2, and 3 shows for the example that the potential of approximately 6 tons for a pile driven without predrilling is reduced to approximately 4 tons by predrilling and approximately 0.5 tons by surrounding pile with a shell.

DEPTH BELOW GROUND SURFACE IN FT.	AVERAGE DEPTH BELOW GROUND SURFACE IN FT.	OVERBURDEN PRESSURE KIPS/SQ. FT.	AVERAGE SHEAR STRENGTH KIPS/SQ.FT.	LATERAL PRESSURE FOR FRICTION KIPS/SQ. FT.	AVERAGE FRICTION KIPS/SQ. FT.	PILE VALUE IN KIPS — PENETRATION IN FEET 16	26	36	46	
0										
	2¼	.305	.198	.458	.114	1.40	1.55	1.70	1.84	
5										
	6½	.717	.465	1.076	.268	1.89	2.10	2.31	2.52	
8										
	10	.897	.243	1.345	.165	1.48	1.61	1.83	2.01	
12										
	14	1.045	.253	1.568	.193	1.66	1.84	2.06	2.26	
16										
						6.43	7.10	7.90	8.63	DOWNDRAG

COMPUTATION FOR DOWNDRAG AND SUPPORT WHEN PREDRILLING IS USED

Table 2

DEPTH BELOW GROUND SURFACE IN FT.	AVERAGE DEPTH BELOW GROUND SURFACE IN FT.	OVERBURDEN PRESSURE KIPS/SQ. FT.	AVERAGE SHEAR STRENGTH KIPS/SQ.FT.	LATERAL PRESSURE FOR FRICTION KIPS/SQ. FT.	AVERAGE FRICTION KIPS/SQ. FT.	PILE VALUE IN KIPS — PENETRATION IN FEET 16	26	36	46	
0										
	2½	.305	.198	.120	.030	.37	.41	.45	.48	
5										
	6½	.717	.465	.065	.016	.11	.13	.14	.15	
8										
	10	.897	.243	.065	.016	.14	.16	.18	.19	
12										
	14	1.045	.253	.065	.016	.14	.15	.17	.19	
16										
						.76	.85	.94	1.01	DOWNDRAG

COMPUTATION FOR DOWNDRAG AND SUPPORT WHEN PILE IS SURROUNDED BY A SHELL

Table 3

The calculation of downdrag forces on piles cannot be considered as yielding precisely the "correct" value. The method is rational, but the lateral pressure which may be developed against a pile undoubtedly is influenced by other factors than the shear strength of the soil. A need exists for the measurement of downdrag forces in actual pile installations. Data from such measurements would be particularly useful in improving the accuracy of estimated downdrag forces. ■

REFERENCES

1. William W. Moore, "Experiences with Predetermining Pile Lengths," Transactions, American Society of Civil Engineers, 1949, Volume 114, pages 351-393.
2. Karl Terzaghi, "Theoretical Soil Mechanics," John Wiley and Sons, pages 69-73.