FOREWORD

IN the following pages is given a condensed and rearranged translation of "Errdruck, Erwiderstand und Tragfahigkeit des Baugrundes Gesichtspunkte fur die Berechnung" by Dr. Ing. H. Krey, published in Germany in 1926. In this book is set forth a system of design generally accepted as modern practice in Europe. Dr. Krey maintains that, since the basic assumptions of earth conditions are theoretical and may vary, to introduce subsequent calculations based on higher mathematics, or to carry out the figures into decimals, is useless because of the original inaccuracy.

The lateral loads on a steel sheet piling wall, as determined by the Krey principles, are somewhat less than those derived by the Rankine-Coulomb method as set forth on pages 2 to 6. In the former the relieving effect of the friction of the earth upon the wall is taken into account and it is necessary, therefore, to determine this frictional value as well as the weight and angle of repose of the earth. Dr. Krey emphatically recommends that extremely careful tests be made to determine these characteristics of the earth to be dealth with.

The use of the Krey method will result in a saving of material and the following translation is offered to those of the Engineering profession designing steel sheet piling structures who are willing to perform the additional preliminary work necessary in order to avail themselves of this economy.

LATERAL PRESSURES ON WALLS

Retaining walls are subjected to lateral pressures from the following load conditions:

1. Water.
2. Earth.
3. Earth submerged in water.

or a combination at different elevations of:

4. Water and earth submerged in water.
5. Earth and earth submerged in water.

Conditions 2 and 5 may be supporting a surcharge load which produces additional lateral pressure.

In the construction of such walls, steel sheet piling may act as a cantilever and, if the height of the wall is great, it may be braced or tied back to anchors, so as to bring it into the condition of a beam supported at both ends. In any event, the strength of the steel piling between the supports should be sufficient to sustain the lateral pressures, and its penetration into firm soil must be such as to prevent movement at the toe.

1. WATER PRESSURES. The direction of water pressure on an immersed plane is always normal to the plane. The fundamental laws of liquid pressures apply as follows:

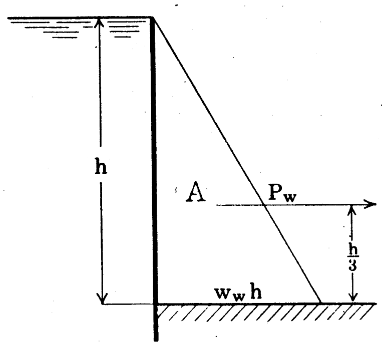


Fig. 1

p_w = pressure in pounds per square foot at depth h.

h = depth of water in feet.

w_w = weight of a cubic foot of water in pounds.

$w_w = 62.5$ for fresh water and 64.0 for salt water.

then,

$$p_w = w_w h.$$

and the total load on the wall, P_w, from the water level to the first support at h feet, is,

$$P_w = \tfrac{1}{2} w_w h^2, \text{ in pounds per foot of width.}$$

The total load is distributed or applied as illustrated in Triangle A, Fig. 1 adjoining.

The total load, P_w, can be considered as concentrated at a distance of $\frac{1}{3}$ h from the bottom. The product $P_w \times \frac{1}{3}$ h is useful in the calculation of the overturning moment in a cellular cofferdam.

The following table will prove useful in giving the values of p_w and P_w for various depths of fresh water.

TABLE 5. HYDROSTATIC PRESSURES
Unit Bottom and Total Pressures on Surface One Foot in Width

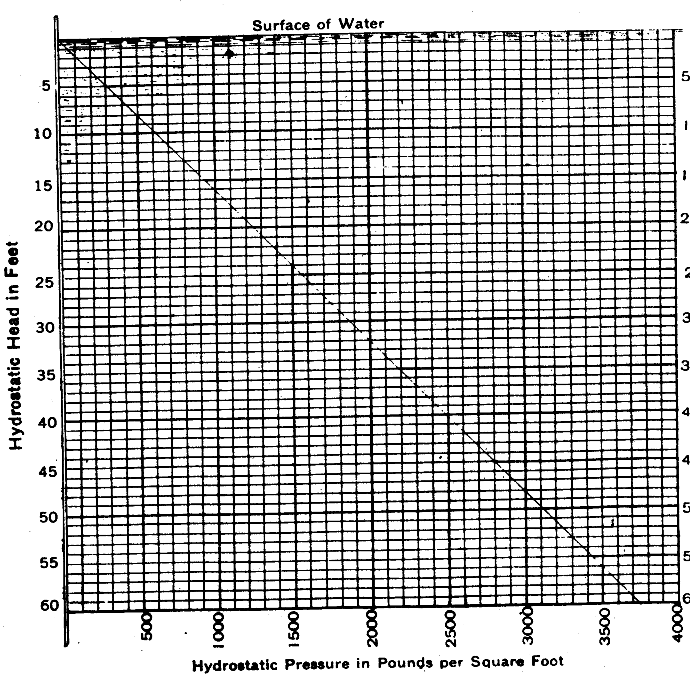


Fig. 2. Diagram of Water Pressures

Depth, feet	Pressure, Pounds Bottom, p_w	Pressure, Pounds Total, P_w	Depth, feet	Pressure, Pounds Bottom, p_w	Pressure, Pounds Total, P_w
1	62.5	31	31	1937.5	30031
2	125	125	32	2000	32000
3	187.5	281	33	2062.5	34031
4	250	500	34	2125	36125
5	312.5	781	35	2187.5	38281
6	375	1125	36	2250	40500
7	437.5	1531	37	2312.5	42781
8	500	2000	38	2375	45125
9	562.5	2531	39	2437.5	47531
10	625	3125	40	2500	50000
11	687.5	3781	41	2562.5	52531
12	750	4500	42	2625	55125
13	812.5	5281	43	2687.5	57781
14	875	6125	44	2750	60500
15	937.5	7031	45	2812.5	63281
16	1000	8000	46	2875	66125
17	1062.5	9031	47	2937.5	69031
18	1125	10125	48	3000	72000
19	1187.5	11281	49	3062.5	75031
20	1250	12500	50	3125	78125
21	1312.5	13781	51	3187.5	81281
22	1375	15125	52	3250	84500
23	1437.5	16531	53	3312.5	87781
24	1500	18000	54	3375	91125
25	1562.5	19531	55	3437.5	94531
26	1625	21125	56	3500	98000
27	1687.5	22781	57	3562.5	101531
28	1750	24500	58	3625	105125
29	1812.5	26281	59	3687.5	108781
30	1875	28125	60	3750	112500

(This is a reprint, of page 1, referring to the law of hydrostatics.)

2. EARTH PRESSURES. Krey's method of calculating earth pressures differs chiefly in the following respects from the Rankine-Coulomb method, given on pages 2 to 6:

(1) Friction of the earth on the wall is taken into account. The line of action of the earth pressure is, therefore, inclined to the horizontal, usually having a downward component, depending on the probable relative motion of the earth and wall at incipient failure.

(2) The total earth pressure, considered as a concentrated load, acts, not at ⅓ the height from the base, as in triangle A, Fig. 1, page 39, but slightly higher than this.

It is considered that, if failure of the wall were to occur, the prism of earth ODE, as illustrated in Fig. 100 adjoining, would slide to the right and downward along plane DO called the "slide line." While doing so, the earth prism would exert on the wall the force P_e at an angle ρ to the normal to the wall surface, (or to the horizontal if the wall is vertical), equal to the friction angle of the earth on the wall. In order to resist failure, this force would have to be balanced by the equal and opposite resistance of the wall, namely the force R. For the earth wedge ODE to be in equilibrium, its weight W_e must be balanced by two other forces, the resistance R of the wall and the force Q exerted on it by the earth underneath.

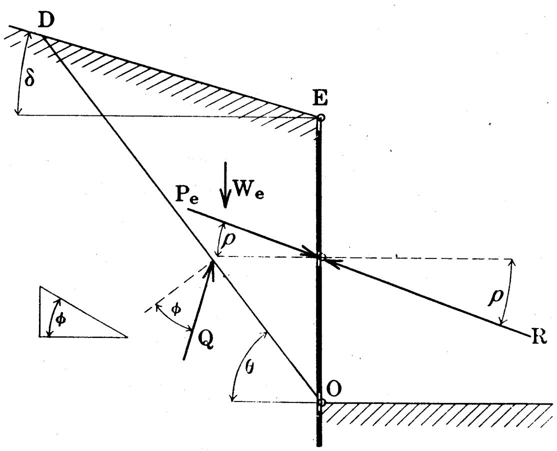


Fig. 100

For equilibrium, therefore, if the sliding surface is to be considered a plane,

$$P_e = -R = W_e \frac{\sin(\quad - \phi)}{\cos(\theta - \phi - \rho)}.$$

Force Q acts at an angle ϕ to the normal to the surface on which sliding occurs, and ϕ is the friction angle of earth on earth, or the natural angle of repose. The angle θ of the "slide line" is unknown and is not the same as the angle of repose ϕ. The weight W_e is also unknown, depending on the angle θ. The initially unknown angle θ which the "slide line" makes with the horizontal is determined as that angle for which the force $P_e = -R$ is a maximum.

There are several methods of finding the maximum P_e for any combination of angles ϕ, ρ, and δ, all of which, however, are complicated. To avoid making these involved calculations for each case, the maximum values of earth pressure coefficients have been determined for many different combinations of angles, and are tabulated as dimensionless numbers in Tables 30, 31, and 32 following, denoted by the symbol K.

As explained more fully on page 43, the variation of the unit earth pressure with depth is not represented exactly by a straight line, but by a slightly curved line, as at the right of the dotted line in Fig. 101. This means, in strict accuracy, that the increment of the pressure is not constant as in the Rankine-Coulomb method (page 2, paragraph 2(a)) but is somewhat greater near the top than near the bottom. For practical purposes, however, Krey assumes that the difference is negligible and that the total pressure is proportional to the square of the depth. On that basis, the increment can also be assumed as constant over the whole depth. Furthermore, while the earth pressure has a downward component, he assumes that it can, for practical purposes, be taken as acting horizontally (see page 44).

The earth pressure may then be transferred to an equivalent horizontal liquid pressure as follows: If p_e is the increment, in pounds per square foot, corresponding to p_w for water, then

$$p_e = K\ w_e.$$

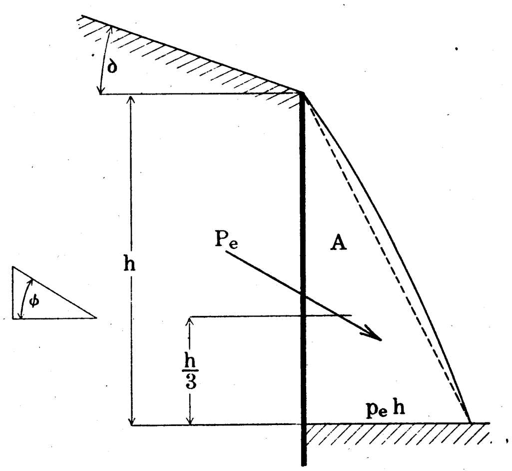


Fig. 101

The fundamental laws of liquid pressures then apply, and the pressure in pounds per square foot at depth h, in feet, is

$$p_e\ h.$$

The total load on the wall P_e, in pounds per foot of width, is

$$P_e = K\ w_e \frac{h^2}{2} = p_e \frac{h^2}{2}.$$

The total load is distributed or applied as shown by the modified triangle A, Fig. 101 adjoining.

TABLE 30. EARTH PRESSURE COEFFICIENTS—K

Wall Vertical
$\delta = +0$

Earth Surface Horizontal
ρ Positive (Pressure has Downward Component)

Values of K for Active Earth Pressure

Angle, ρ +	Angle of repose, ϕ: 15°	17° 30′	20°	22° 30′	25°	27° 30′	30°	32° 30′	35°	37° 30′	40°	42° 30′	45°	50°	60°	Angle, ρ +
0°	0.590	0.539	0.491	0.449	0.406	0.369	0.334	0.301	0.272	0.242	0.216	0.192	0.170	0.132	0.072	0°
5°	0.557	0.510	0.466	0.424	0.386	0.351	0.318	0.288	0.261	0.233	0.208	0.185	0.164	0.129	0.070	5°
10°	0.534	0.489	0.448	0.409	0.372	0.340	0.309	0.281	0.253	0.227	0.202	0.180	0.160	0.126	0.068	10°
15°	0.517	0.474	0.435	0.398	0.364	0.332	0.302	0.274	0.248	0.222	0.198	0.177	0.158	0.125	0.067	15°
17° 30′	......	0.469	0.431	0.395	0.361	0.330	0.301	0.272	0.247	0.221	0.198	0.176	0.158	0.125	0.066	17° 30′
20°	......	......	0.428	0.398	0.358	0.328	0.300	0.271	0.246	0.220	0.197	0.175	0.157	0.125	0.066	20°
22° 30′	......	......	......	0.391	0.358	0.327	0.299	0.271	0.246	0.221	0.197	0.176	0.157	0.126	0.066	22° 30′
25°	......	......	......	......	0.357	0.327	0.298	0.271	0.246	0.222	0.198	0.177	0.158	0.126	0.066	25°
27° 30′	......	......	......	......	......	0.327	0.298	0.272	0.247	0.222	0.198	0.178	0.159	0.127	0.066	27° 30′
30°	......	......	......	......	......	......	0.297	0.273	0.248	0.223	0.199	0.179	0.160	0.128	0.067	30°
32° 30′	......	......	......	......	......	......	......	0.275	0.250	0.225	0.201	0.181	0.162	0.130	0.068	32° 30′
35°	......	......	......	......	......	......	......	......	0.252	0.228	0.203	0.184	0.164	0.132	0.069	35°
37° 30′	......	......	......	......	......	......	......	......	......	0.231	0.207	0.187	0.167	0.134	0.071	37° 30′
40°	......	......	......	......	......	......	......	......	......	......	0.211	0.190	0.171	0.136	0.073	40°
42° 30′	......	......	......	......	......	......	......	......	......	......	......	0.194	0.174	0.138	0.076	42° 30′
45°	......	......	......	......	......	......	......	......	......	......	......	......	0.178	0.140	0.078	45°
50°	......	......	......	......	......	......	......	......	......	......	......	......	......	0.143	0.086	50°
60°	......	......	......	......	......	......	......	......	......	......	......	......	......	......	0.098	60°

TABLE 31. EARTH PRESSURE COEFFICIENTS—K

Wall Vertical
$\delta = +10°$

Earth Surface Inclined at an Angle to Horizontal
ρ **Positive** (Pressure has Downward Component)

Values of K for Active Earth Pressure

ANGLE, ρ +	ANGLE OF REPOSE, ϕ															ANGLE, ρ +
	15°	17° 30′	20°	22° 30′	25°	27° 30′	30°	32° 30′	35°	37° 30′	40°	42° 30′	45°	50°	60°	
0°	0.71	0.63	0.57	0.51	0.46	0.42	0.37	0.33	0.30	0.27	0.23	0.21	0.19	0.14	0.08	0°
5°	0.68	0.61	0.54	0.49	0.44	0.41	0.36	0.32	0.29	0.26	0.23	0.21	0.18	0.14	0.08	5°
10°	0.67	0.59	0.53	0.48	0.43	0.40	0.35	0.32	0.28	0.25	0.22	0.20	0.18	0.13	0.07	10°
15°	0.66	0.58	0.52	0.47	0.42	0.39	0.34	0.31	0.28	0.25	0.22	0.20	0.18	0.13	0.07	15°
17° 30′	.....	0.57	0.52	0.47	0.42	0.39	0.34	0.31	0.28	0.25	0.22	0.20	0.18	0.13	0.07	17° 30′
20°	.....	.....	0.51	0.47	0.42	0.39	0.34	0.31	0.27	0.25	0.22	0.20	0.17	0.13	0.07	20°
22° 30′	.....	.....	.....	0.47	0.42	0.39	0.34	0.31	0.28	0.25	0.22	0.20	0.18	0.13	0.07	22° 30′
25°	.....	.....	.....	.....	0.42	0.39	0.35	0.31	0.28	0.25	0.22	0.20	0.18	0.13	0.07	25°
27° 30′	.....	.....	.....	.....	.....	0.39	0.35	0.32	0.28	0.25	0.22	0.20	0.18	0.13	0.08	27° 30′
30°	.....	.....	.....	.....	.....	.....	0.35	0.32	0.28	0.25	0.23	0.20	0.18	0.13	0.08	30°
32° 30′	.....	.....	.....	.....	.....	.....	.....	0.32	0.29	0.25	0.23	0.20	0.18	0.13	0.08	32° 30′
35°	.....	.....	.....	.....	.....	.....	.....	.....	0.29	0.26	0.23	0.20	0.18	0.13	0.08	35°
37° 30′	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.26	0.24	0.21	0.18	0.13	0.08	37° 30′
40°	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.24	0.21	0.19	0.14	0.09	40°
42° 30′	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.21	0.19	0.14	0.09	42° 30′
45°	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.19	0.14	0.09	45°
50°	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.15	0.10	50°
60°	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.11	60°

TABLE 32. EARTH PRESSURE COEFFICIENTS—K

Wall Vertical
$\delta = +30°$

Earth Surface Inclined at an Angle to Horizontal
ρ **Positive** (Pressure has Downward Component)

Values of K for Active Earth Pressure

ANGLE, ρ +	ANGLE OF REPOSE, ϕ							ANGLE, ρ +
	35°	37° 30′	40°	42° 30′	45°	50°	60°	
0°	0.434	0.372	0.318	0.274	0.236	0.171	0.086	0°
5°	0.426	0.365	0.312	0.268	0.231	0.168	0.085	5°
10°	0.421	0.360	0.307	0.264	0.228	0.166	0.084	10°
15°	0.420	0.358	0.306	0.262	0.226	0.165	0.084	15°
17° 30′	0.421	0.358	0.305	0.262	0.226	0.165	0.084	17° 30′
20°	0.423	0.360	0.306	0.263	0.227	0.165	0.084	20°
22° 30′	0.426	0.362	0.307	0.264	0.228	0.166	0.084	22° 30′
25°	0.430	0.364	0.309	0.265	0.230	0.167	0.084	25°
27° 30′	0.435	0.368	0.311	0.267	0.231	0.168	0.085	27° 30′
30°	0.440	0.372	0.315	0.270	0.233	0.170	0.086	30°
32° 30′	0.447	0.378	0.320	0.273	0.237	0.172	0.088	32° 30′
35°	0.455	0.384	0.324	0.278	0.240	0.175	0.090	35°
37° 30′	....	0.392	0.330	0.282	0.245	0.178	0.092	37° 30′
40°	....	....	0.336	0.289	0.250	0.181	0.094	40°
42° 30′	....	....	....	0.295	0.255	0.185	0.096	42° 30′
45°	....	....	....	....	0.261	0.190	0.100	45°
50°	....	....	....	....	....	0.202	0.106	50°
60°	....	....	....	....	....	....	0.125	60°

The values to be used for the unit weight of the earth w_e, the angle of repose ϕ, and the friction angle ρ of the earth on the wall should be determined in every case by an actual test of the particular kind of earth encountered. The angle of repose can be found by heaping up a pile of the material and measuring the greatest angle of the sides of the pile. If the earth will be entirely or partly submerged, the angle should be measured in water also, since this usually decreases the friction.

The friction angle ρ of the earth on the wall depends to some extent on the roughness of the latter as well as on the nature of the soil. It can never exceed the earth-on-earth friction angle ϕ, but may vary between $+\ \phi$ and zero. This angle can be determined by test, but may be estimated closely enough from the value of ϕ, when this has been determined. H. Blum states that the friction angle ρ of earth on steel is $\frac{1}{3}$ to $\frac{1}{2}\ \phi$.

More important than the actual value of this friction angle is the **direction** of the earth pressure, i. e., whether the vertical component acts upward or downward. This can be determined by carefully studying how the wall would move if it started to fail, and in which direction the earth particles would slide on it at various levels. For the majority of cases, the component acts downward, and the K factors given in Tables 30, 31 and 32 are to be used. An exception would be where the earth under the wall is more yielding than the filling behind the wall, in which case the earth pressure might have a steep slope upward.

Careful thought should be given to the possible effect of vibrations. In most cases these are absent, but in the vicinity of railroad tracks, cranes, or when blasting is done nearby, not only may the angle of repose ϕ of the earth itself and the friction angle ρ of the earth on the wall be decreased, but the tamping action of repeated vibrations may so change the pressure conditions that the pressure of the fill behind the wall increases until it is equal to the full weight of the column, or K = unity. For cases where it is known that vibrations are likely to occur, Krey recommends that ϕ be decreased somewhat from the values determined by test, and that ρ be assumed to increase uniformly from zero at the earth surface to its full static value at depth h, or, for simplicity, may be taken as zero over the upper half of the wall and at its full static value over the lower half of the wall.

The effect of submergence in water and of action of vibrations is illustrated by Table 33 following, giving the results of experiments by Krey. *The values are illustrative only and are not to be used in the calculations except as a rough guide. In every case the angle should be determined by tests.*

TABLE 33. VALUES OF FRICTION ANGLE OR ANGLE OF REPOSE ϕ.

Material	Without Vibration		Vibrated
	Dry	Submerged in Water	Dry
	Angle ϕ	Angle ϕ	Angle ϕ
Sieved Sand (Grains 0.036 to 0.048 inch)	32° 30′	32° 30′	30°
River Sand	32° 30′	......	......
Pure, Finely Ground Clay	45°	15°	......

DISTRIBUTION OF EARTH PRESSURES. According to Krey's theory, the distribution of the earth pressures along the height of the wall is not represented exactly by a triangle.

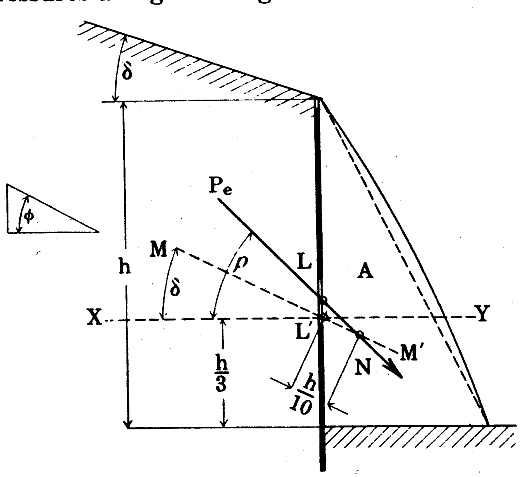


Fig. 102

Instead of the hypotenuse of the triangle being straight, as illustrated by the dotted line, Fig. 102, adjoining, it is the slightly convex, solid line. Consequently, the point of application of the total load P_e, considered as a concentrated force, is not at a distance of $\frac{1}{3}$ h above the bottom, but slightly higher up.

He gives the following empirical method for locating this point of application. See Fig. 102.

At a distance $\frac{1}{3}$ h from the base of the triangle A draw the horizontal line XY, intersecting the contact surface of the earth with sheet piling wall at L′. Through this point draw line MM′ parallel to the upper earth surface, hence at angle δ to the horizontal. On MM′ lay off distance L′N equal to 1/10 the height of the wall. Through point N draw the line of action of the total load or force, P_e, at an angle ρ to the horizontal.

The intersection with the contact surface of the earth and wall at L is the point of application of the total load, P_e.

When there is a surcharge load, the distribution of the combined lateral loads due to the surcharge and earth is illustrated by a trapezoid rather than a triangle, and the line XY is drawn through the center of gravity of the trapezoid (see Fig. 106, page 46). Similarly, when only a section of height h″ of the wall is being considered, the distribution of the lateral load is trapezoidal, and the line XY is drawn through the center of gravity of the trapezoid, while the distance L′N, Fig. 102, page 43 is made equal to 1/10 h″.

Krey recommends that, once the direction and point of application of the total load P_e have been determined, this force be considered as acting horizontally, stating that, in view of the unavoidable uncertainty of the various factors, such a refinement as resolving the force to obtain its horizontal component is hardly justifiable.

(a) Level Bank. The earth pressure is transferred to an equivalent horizontal liquid pressure, p_e, in pounds per square foot, as follows, and p_e is the increment in pounds per square foot corresponding to p_w for water. Then

$$p_e = K\ w_e.$$

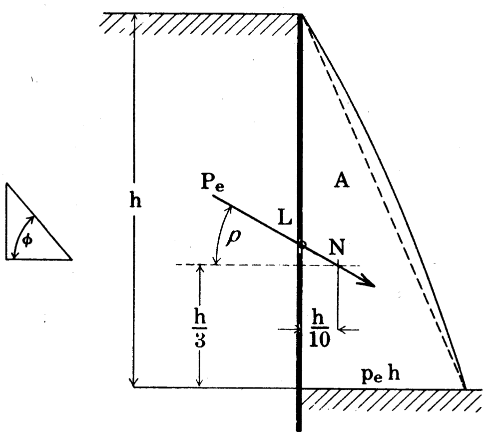


Fig. 103

where w_e = weight per cubic foot of earth in pounds.

and K = coefficient from Table 30 for the angle of repose ϕ of the earth and the friction angle ρ of the earth on the sheet piling wall, as determined by tests of the soil.

The fundamental laws of liquid pressures then apply, which gives, as illustrated in Fig. 103 adjoining, and

$$p_e h \quad \text{or} \quad Kw_e h$$

is the pressure in pounds per square foot at any depth h, in feet.

The total load on the wall, P_e, in pounds per foot of width, is

$$P_e = K\ w_e \frac{h^2}{2} \quad \text{or} \quad P_e = \tfrac{1}{2} p_e h^2.$$

The total load is applied or distributed approximately as illustrated in the modified triangle A in Fig. 103 above, and the point of application of the equivalent concentrated load is at point L.

Example 1. No Vibration.

h = 30 feet.
ϕ = 32° 30′.
ρ = Approximately 2/3 × 32° 30′ = 22°.
w_e = 90 pounds per cubic foot.
K = 0.271, from Table 30.

$$P_e = 0.271 \times 90 \times \frac{30^2}{2} = 10{,}976 \text{ pounds per foot of width.}$$

(This is about 10 per cent lower than if figured by the Rankine-Coulomb method.)

Distance of point of action L above the bottom is

$$\tfrac{1}{3} h + \tfrac{1}{10} h \tan \rho = \frac{30}{3} + \frac{30}{10} \times 0.4040 = 11.21 \text{ feet.}$$

Example 2. With Vibration.

Let the conditions be the same as in Example 1 but subjected to continuous vibration. See Fig. 104. adjoining.

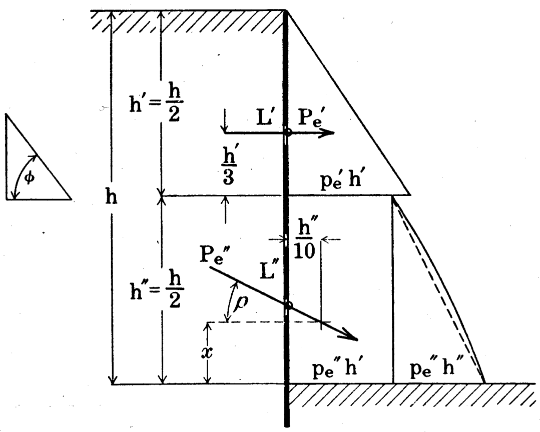


Fig. 104

Let $\phi = 25°$.

$\rho = 0$ on upper half of wall.

$\rho' = \frac{2}{3} \times 25° = 16°$ on lower half of wall.

$h' = 15$ feet.

$h'' = 15$ feet.

For upper half of wall,

K = 0.406, from Table 30.

$$P_e' = 0.406 \times 90 \times \frac{15^2}{2} = 4{,}110 \text{ pounds per foot of width.}$$

This is the total pressure in pounds per foot of width acting at a distance from the bottom of $15 + \frac{15}{3} = 20$ feet.

For lower half of wall,

From Table 30, by interpolation, K = 0.363.

Pressure at top of bottom section, $p_e'' h' = 0.363 \times 90 \times 15 = 490$ pounds per square foot.

Pressure at bottom of bottom section,

$p_e'' h' + p_e'' h'' = 490 + 0.363 \times 90 \times 15 = 490 + 490 = 980$ pounds per square foot.

Total pressure on lower half of wall, $P_e'' = 490 \times 15 + 490 \times \frac{15}{2} = 11{,}025$ pounds per foot of width.

Total pressure on entire wall, $= 11{,}025 + 4{,}110 = 15{,}135$ pounds per foot of width. This is almost 50 per cent greater than for Example 1.

Distance x, center of gravity of trapezoid from base, Fig. 104, above,

$$x = \frac{h''}{2} \times \left(\frac{p_e'' h' + \frac{1}{3} p_e'' h''}{p_e'' h' + \frac{1}{2} p_e'' h''}\right) = \frac{15}{2} \times \left(\frac{490 + \frac{1}{3} \times 490}{490 + \frac{1}{2} \times 490}\right) = 6.67 \text{ feet.}$$

Distance of point of application of the total load P_e'' from the bottom,

$$x + \frac{h''}{10} \tan \rho = 6.67 + \frac{15}{10} \tan 16° = 7.10 \text{ feet.}$$

(b) Inclined Bank. The same method applies in this case but the values of K are taken from Tables 31 and 32, for inclination angles, δ, of + 10° and + 30° respectively. For other angles the values of K are obtained by interpolation between the values in Tables 30 and 31, or 31 and 32.

The problem is illustrated in Fig. 105, adjoining.

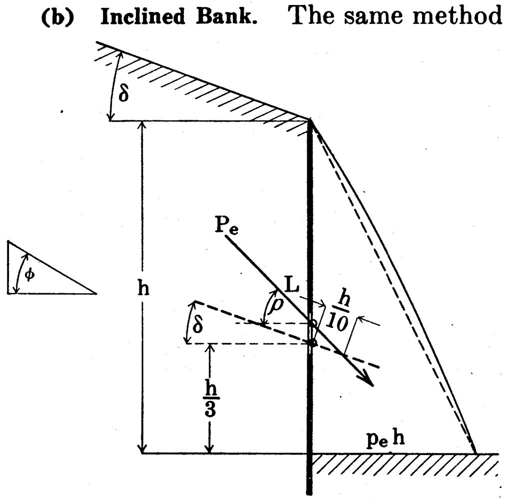


Fig. 105

Example 3.

$h = 25$ feet.

$\phi = 32° 30'$.

$\delta = 20°$.

$\rho = 32° 30'$.

$w_e = 95$ pounds per cubic foot.

From Table 31, for $\delta = +10°$, $K = 0.32$ for these angles and from Table 32, for $\delta = +30°$, $K =$ (about) 0.50. Interpolating between these values for $\delta = +20°$, $K = 0.41$ approximately.

$$P_e = K\,w_e\frac{h^2}{2} = 0.41 \times 95 \times \frac{25^2}{2} = 12{,}180 \text{ pounds per foot of width.}$$

Distance of point of application of total load, P_e, above bottom,

$$\frac{h}{3} - \frac{h}{10}\sin\delta + \frac{h}{10}\cos\delta\tan\rho =$$

$$25 \times (1/3 - 1/10 \sin 20° + 1/10 \cos 20° \tan 32°\,30') = 8.97 \text{ feet.}$$

(c) **Surcharge Load.** For the case of a surcharge load, Krey's method does not differ in principle from the method previously explained on page 2. In detail it differs to the extent that the surcharge load is considered equivalent to an additional load for height equal to

$$\frac{w_s}{w_e} = h', \text{ in feet,}$$

in which w_s is the surcharge load in pounds per square foot, and w_e is the weight of the earth in pounds per cubic foot.

The lateral pressure p_s, in pounds per square foot, due to the surcharge alone, is

$$p_s = h'\,K\,w_e, \quad \text{or} \quad p_s = K\,w_s,$$

where K = coefficient from Table 30.

The lateral pressure p_s is not subject to the laws of liquid pressures but is a uniform load throughout the height h, in feet, of the piling wall; and the total load, in pounds per foot of width, due to the surcharge is

$$P_s = p_s\,h.$$

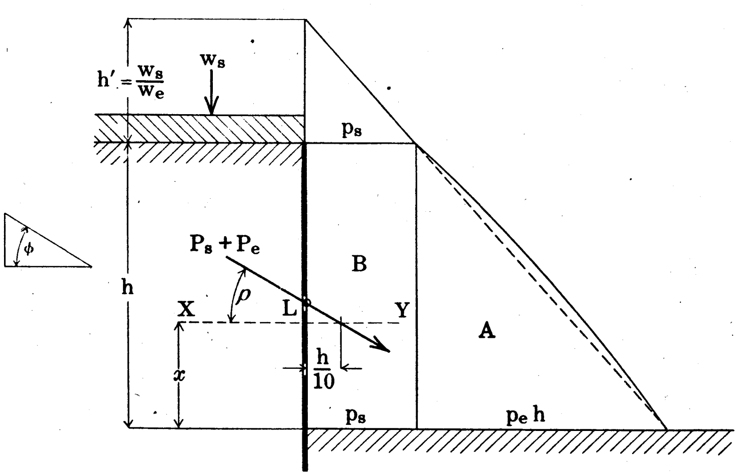


Fig. 106

Figure 106, adjoining, shows a piling wall which retains earth pressure and is loaded with a surcharge of railroad cars or piled materials which increases the lateral pressure. The total load, due to the surcharge alone, is applied or distr buted as illustrated in rectangle B.

The lateral loads, due to the earth loads alone are calculated as described in (a) preceding, and since this pressure is liquid, the total load for these earth loads is illustrated in modified triangle A.

The pressure, in pounds per square foot, at any point h feet from the top of the wall, due to surcharge and earth is, therefore,

$$p_s + p_e\,h = K\,(w_s + w_e\,h),$$

where K = coefficient from Table 30.

The total lateral load on the wall, in pounds per foot of width, is

$$P_s + P_e = K\ w_s\, h + K\ w_e \frac{h^2}{2}.$$

The line of action of this combined load or force passes through point L at a distance in feet from the bottom equal to

$$\frac{h}{2} \times \left(\frac{p_s + \frac{1}{3}\, p_e\, h}{p_s + \frac{1}{2}\, p_e\, h}\right) + \frac{h}{10} \tan \rho.$$

Example 4.

w_s = 750 pounds per square foot
w_e = 90 pounds per cubic foot.
ϕ = 30°.
ρ = 20°.
h = 30 feet.
K = .300, from Table 30.

$\frac{w_s}{w_e} = \frac{750}{90} = 8\frac{1}{3}$ feet, height of an equivalent column of earth.

$p_s = 8\frac{1}{3} \times .300 \times 90$ or $.300 \times 750 = 225$ pounds per square foot.
Total load, in pounds per foot of width, is

Due to earth	$.300 \times 90 \times \frac{30^2}{2}$	= 12,150	pounds.
Due to surcharge	225×30	= 6,750	"
	Total Load	18,900	"

$$\text{Height of L from bottom} = \frac{30}{2} \times \left(\frac{750 + \frac{1}{3} \times 30 \times 90}{750 + \frac{1}{2} \times 30 \times 90}\right) + \frac{30}{10} \tan 20° = 12.87 \text{ feet.}$$

3. EARTH SUBMERGED IN WATER. Krey's method of allowing for the effect of submergence of earth in water is exactly the same in principle as already explained in assumption 2 on page 4, that is, the full hydrostatic pressure is assumed to act horizontally and the weight of earth is reduced by the amount of the buoyancy produced by the water. Thus if v is the percentage of voids in the material, w_e the weight of the dry earth, and w_w, the weight of water, then the submerged weight of the earth in pounds per cubic foot is

$$w_{e\ in\ w} = w_e - \frac{(100 - v)}{100} w_w.$$

(a) Submerged Earth on One Side Only.

Let $w_{e\ in\ w}$ = weight, in pounds, of a cubic foot of earth submerged in water.

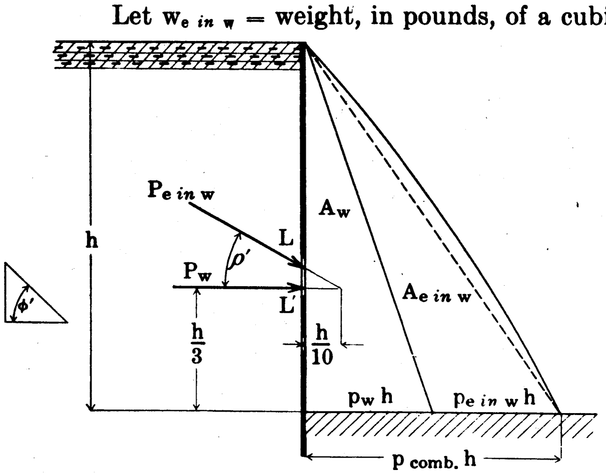


Fig. 107

The problem is illustrated in Fig. 107, adjoining.

The pressure due to water only (see paragraph 1, page B-18), in pounds per square foot at depth h, in feet, is

$$p_w = w_w\, h$$

where w_w = 62.5 pounds for fresh water and 64.0 pounds for salt water.

The pressure due to submerged earth only, at depth h feet, is

$$p_{e\ in\ w} = K'\ w_{e\ in\ w}\, h.$$

where K′ is coefficient from Table 30 for the angles ϕ' and ρ' appropriate for earth submerged in water.

The total pressure, p omb, due to water and submerged earth, in pounds per square foot at depth h feet are not added directly, since they do not act in the same direction. Approximately, however,

$$p_{comb.} = w_w h + K' w_{e\ in\ w} h,$$

The total load due to water only, in pounds per foot of width, is

$$P_w = \tfrac{1}{2} w_w h^2$$

This acts horizontally at a point ⅓ h above the lower earth level and is applied or distributed as illustrated in triangle A_w in Fig. 107, page 47.

The total load due to submerged earth only, in pounds per foot of width, is

$$P_{e\ in\ w} = K' w_{e\ in\ w} \frac{h^2}{2},$$

This load, applied or distributed as illustrated in modified triangle $A_{e\ in\ w}$, acts at angle ρ' to the horizontal through point L at a distance of

$$\frac{h}{3} + \frac{h}{10} \tan \rho' \text{ feet above the bottom.}$$

and the total combined load due to earth and water is

$$P_{comb.} = P_w + P_{e\ in\ w}$$

Example 5.

w_w	= 62.5 pounds per cubic foot.
w_e (dry)	= 90.0 " " "
v (voids in earth)	= 40 percent.
ϕ'	= 25°.
ρ'	= 17° 30′.
h	= 25 feet.
K	= 0.361, from Table 30.

$$w_{e\ in\ w} = 90 - \frac{100 - 40}{100} \times 62.5 = 52.5 \text{ pounds per cubic foot.}$$

The load due to water is

$$P_w = 62.5 \times \frac{25^2}{2} = 19{,}530 \text{ pounds per foot of width.}$$

acting at a distance of $\frac{25}{3} = 8.33$ feet from the bottom.

The load due to submerged earth only, is

$$P_{e\ in\ w} = 0.361 \times 52.5 \times \frac{25^2}{2} = 5{,}923 \text{ pounds per foot of width.}$$

This load acts at an angle of 17° 30′ to the horizontal at a distance of

$$8.33 + \frac{25}{10} \tan 17° 30' = 9.12 \text{ feet from the bottom.}$$

Approximately, the two separate loads can be considered as replaced by a single load

$$P_{comb.} = P_w + P_{e\ in\ w} = 19{,}350 + 5{,}923 = 25{,}453 \text{ pounds per foot of width.}$$

(b) Submerged Earth on One Side, Water on Other Side.

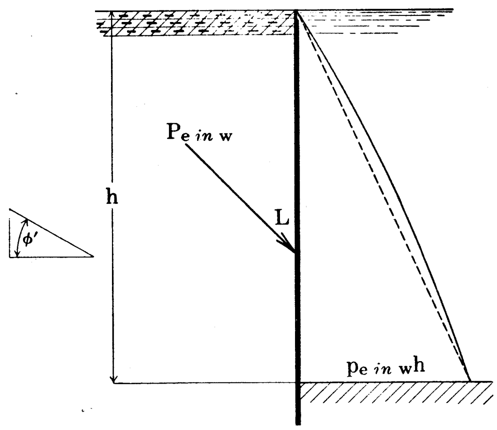


Fig. 108

Fig. 108, adjoining, illustrates the problem.

The water pressures on the two sides balance; hence, the total pressure is that of the submerged earth only.

The pressure per square foot at any depth h feet is, therefore,

$$p_{e\ in\ w} = K'\, w_{e\ in\ w}\, h.$$

The total lateral pressure, in pounds per foot of width, is

$$P_{e\ in\ w} = K'\, w_{e\ in\ w}\, \frac{h^2}{2}.$$

K′ is the coefficient from Table 30 for the appropriate values of ϕ' and ρ'.

The location of the point of application L is outlined on page 43.

4. **COMBINATIONS OF WATER AND EARTH SUBMERGED IN WATER.** The problem of calculating the loads for the various combinations resolves itself into reducing all of the individual conditions, which cause the lateral load on the wall, to the individual lateral loads. For all except a surcharge load, this means to their equivalent liquid pressures. The individual loads are combined, after each one is studied as before described, and the total load laterally on the wall, for the most usual conditions, are best illustrated by the following sketches with the load diagrams.

The symbols shown in the sketches have been developed in the three preceding paragraphs but for convenient reference they are summarized as follows:

All heights (h and h′) are in feet; all pressures (P, etc.) are in pounds per square foot; all angles in degrees

Equivalent Liquid Lateral Pressures

p_w = Water.
p_e = Earth only
$p_{e\ in\ w}$ = Earth submerged in water.
$p_{comb.}$ = Combined water and earth submerged in water.

Uniformly Distributed Lateral Pressure

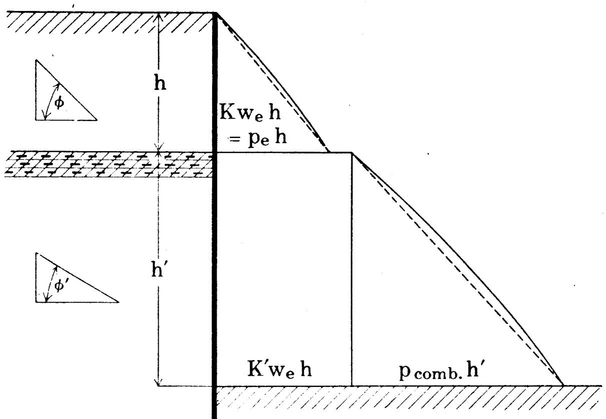
p_s = Due to surcharge load w_s, in pounds per square foot.

Angles

ϕ = Angle of repose of earth.
ϕ' = Angle of repose of earth submerged in water.
ρ = Friction angle of earth on steel sheet piling wall.
ρ' = Friction angle of earth submerged in water on steel sheet piling wall.

Lateral Pressure Coefficients

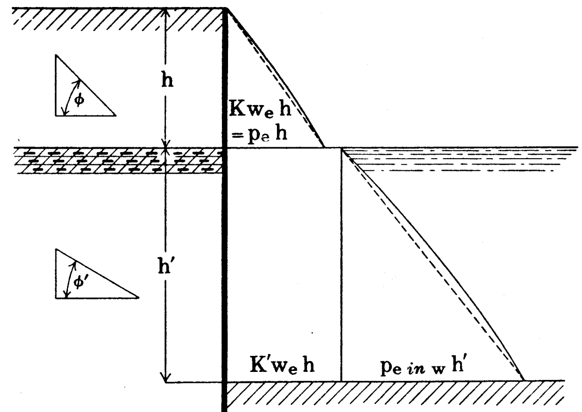
K = Coefficient as read from Table 30 for angles ϕ and ρ.
K′ = Coefficient for earth submerged in water as read from Table 30 for angles ϕ' and ρ'.



$p_{comb.}\,h' = (w_w + K'\,w_{e\ in\ w})\,h'$

Fig. 109

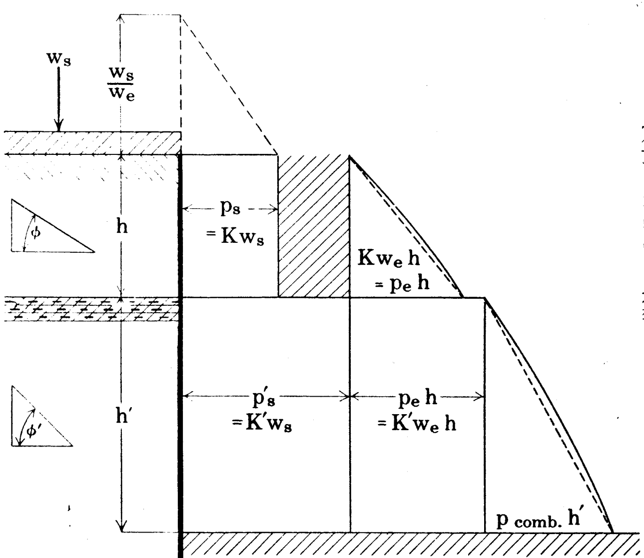
Dry Earth over Submerged Earth on One Side.



$p_{e\ in\ w}\,h' = K'\,w_{e\ in\ w}\,h'$

Fig. 112

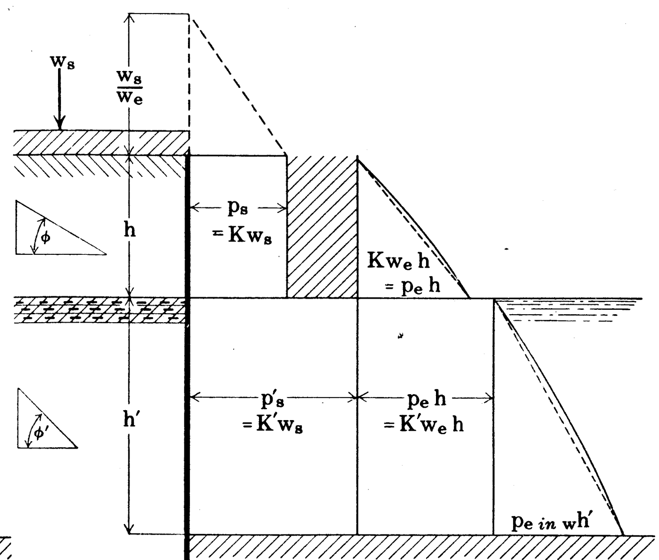
Dry Earth over Submerged Earth, Water on Opposite Side.



$p_{comb.}\,h' = (w_w + K'\,w_{e\ in\ w})\,h'$

Fig. 110

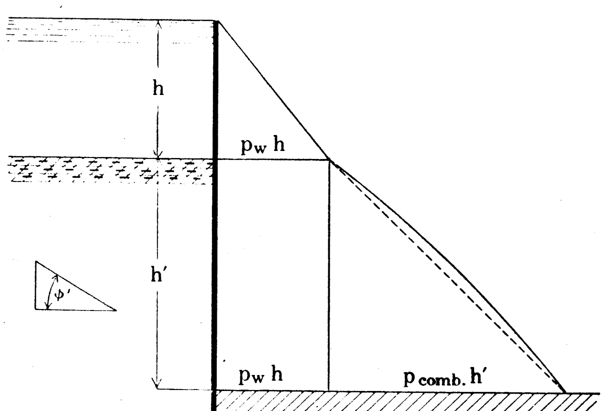
Surcharge on Dry Earth over Submerged Earth on One Side.



$p_{e\ in\ w}\,h' = K'\,w_{e\ in\ w}\,h'$

Fig. 113

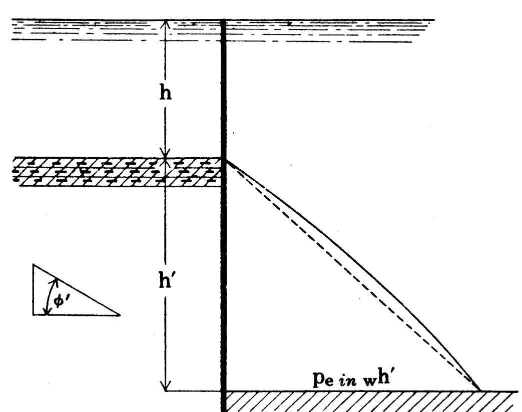
Surcharge on Dry Earth over Submerged Earth, Water on Opposite Side



$p_{comb.}\,h' = (w_w + K'\,w_{e\ in\ w})\,h'$

Fig. 111

Water on Top of Submerged Earth on One Side.



$p_{e\ in\ w}\,h' = K'\,w_{e\ in\ w}\,h'$

Fig. 114

Water on Top of Submerged Earth, Water on Opposite Side.

After the lateral loads on the sheet piling wall have been determined by the above methods the subsequent procedure leading to the final design of the sheet piling structure is outlined on pages 7 to 14 and 25 to 37.