Several soils, when piles are driven in, show only an apparent penetration. Therefore it is necessary to repeat the dynamic test several days after the driving. The parameter then is determined in accordance with the penetration of the piles from one stroke of the hammer, with the so-called supplementary driving of the piles. From formula (4) we have

$$p = ey \quad ....(4')$$

From the parabolic character of the driving curve it can be concluded that the specific resistance of the pile almost does not change with the depth of driving, i.e.

$$A = A' + A'' = \frac{R}{Y} = \sim \text{ a constant} \tag{10}$$

A' - resistance of the lateral surface;

A" - resistance of the end of the pile.

The character of changes in the normal stresses along the axis of the pile is determined by Fig. 13 in which

$$y = \frac{P}{A'} .$$

The linear deformation of the pile will then be:

$$\Delta L = \Delta h + \Delta y = \frac{Ph}{E\ F} + \frac{P^2}{2A'E\ F} \tag{11}$$

Fig. 14 shows the result of the loading of test pile N 2 in Gorkyi. The end of this pile stuck in dense marl and did not show settlement. To a load of P = 50.0 tons corresponds a deformation L = 4.5 mm and with formula (11) was found A' = 4.00 T/M. After this, according to the formula, the theoretical curve was constructed (Fig. 15).

Fig. 16 shows the comparison of this curve with the real curve of determination of pile N 5. Up to the limit of elasticity the coincidence is good.

No. H-6 NOTES ON THE PILE DRIVING FORMULA INCLUDED IN THE PROPOSED BOSTON BUILDING CODE

J. Stuart Crandall, President, Crandall Dry Dock Engineers, Cambridge, Massachusetts

zie ook "Proceedings Am. Soc. Civ. Eng. December 1937 - Vol 63 no 10 blz 1980"

In the proposed revised building code for the City of Boston, Massachusetts, U.S.A. (Paper No.Z-17) attempt has been made to provide, so far as is practically possible in regulations, for the three essential requirements for a pile foundation, namely:

1. That the material forming the piles is not over-stressed.
2. That the soil supporting the piles is not over-loaded.
3. That the load on each individual pile is less than its resistance to penetration in the soil.

The method of meeting the first two requirements is evident from a perusal of the Chapter (Paper Z-17). The third requirement is met by providing for the use of a modification of Hiley's formula, application of load tests or both. Previously there had been no provisions for the first two requirements and only the third was regulated by requiring the calculation of driving resistance by the Engineering News formula and by requiring loading tests.

The pile driving formula is based on the following nomenclature, and the modification consists in assuming the coefficient of restitution, (n), = 0, and applying a factor of safety of 3.

R_d = dynamic resistance
R = allowable load
W = weight of striking parts of hammer
P = weight of pile as driven
h = height of fall of hammer
s = penetration of pile per blow
E = modulus of elasticity of pile as driven
A = cross-section area of pile as driven
L = length of pile as driven
n = coefficient of restitution
e = efficiency of hammer
= 0.75 for usual drop hammer
= 0.90 for single acting steam hammer
2C = elastic compression of driving cap
$2C_1$ = elastic compression of pile as driven

$2C_2$ = rebound of pile due to elastic compression of soil and other causes
$2k$ = total rebound of pile hammer
eWh = available energy at instant of impact

$$R_d\ (C + C_1 + C_2) = R_d k = \text{total energy loss}$$

$$R_d s = eWh - eWh\ \frac{P(1 - n^2)}{W + P} - R_d k \qquad (1)$$

$$R_d = \frac{eWh}{s + k} \times \frac{W + n^2 P}{W + P} \qquad \text{Hiley's formula} \qquad (2)$$

Inasmuch as the value of "n" is about 0.2 for cast iron or steel on wood (there being usually the two materials in impact) and "n" appearing squared in the formula, it seems reasonable to assume n = 0 then

$$R_d = \frac{eWh}{s + k} \times \frac{W}{W + P} \qquad (3)$$

Provided the actual resistance to driving may be obtained, a factor of safety of 3 seems reasonable. Applying this factor and the values for "e"

$$R = \frac{0.25\ Wh}{s + k} \times \frac{W}{W + P} \qquad \text{drop hammer} \qquad (4)$$

$$R = \frac{0.3\ Wh}{s + k} \times \frac{W}{W + P} \qquad \text{steam hammer single acting} \qquad (5)$$

Measuring drop of hammer in feet and penetration in inches, these became:

$$R = \frac{3\ Wh}{s + k} \times \frac{W}{W + P} \qquad \text{drop hammer} \qquad (6)$$

$$R = \frac{3.6\ Wh}{s + k} \times \frac{W}{W + P} \qquad \text{steam hammer single acting} \qquad (7)$$

Here all the terms are known except $k = C + C_1 + C_2$

$$C_1 = 1/2\ \frac{R_d L}{EA} = \frac{3}{2}\ \frac{RL}{EA} \qquad (8)$$

assuming the extreme case of point bearing pile.

The value of 2C varies with the type of driving cap and its condition. Based on Hiley's experiments the value is arbitrarily assumed equal to 0.10 inches (2.5 m/m).

The value of C_2 is ordinarily indeterminate and is neglected. (This is probably compensated by the assumption for C_1), hence:

$$k = \frac{3}{2}\ \frac{RL}{EA} + 0.05 \qquad (9)$$

Paper No.Z-17 gives tabulated values for k, in inches, for different types of piles of varying lengths and capacities.

The following table gives the allowable loads calculated by formulas (6) and (7) compared with subsequent load tests.

Now if equation (1) be solved for h

$$h = \frac{R_d s + R_d k}{eW} \times \frac{W + P}{W + n^2 P} \qquad (10)$$

It is evident that for any given case there is a height and fall of hammer, h_o, below which the pile does not move, i.e., s = 0

$$\text{when } s = 0 \qquad h = h_o = \frac{R_d k}{eW} \times \frac{W + P}{W + n^2 P} \qquad (11)$$

substituting in (.10)

$$h = \frac{R_d s}{eW} \times \frac{W + P}{W + n^2 P} + h_o \qquad (12)$$

then

$$R_d = \frac{eW(h - h_o)}{s} \times \frac{W + n^2 P}{W + P} \qquad (13)$$

Identification	Description of Pile, Hammer, & Soil.	Dimensions			Weight		Driving		Bearing capacity form. 6 & 7 tons		Load Test			Remarks
		Butt - in.	Tip - in.	Length - ft.	Pile - tons	Hammer - tons	Drop - ft.	Penetr. - in.	All.	Ult.	Load - tons	Settlement - in.	Pull - tons	
M.I.T. Group A Pile No. 12	Spruce, Drop Hammer thru fill and silt to 12 ft. in fine sand	(11)	(6)	30	0.17	1.15	9	2	12.3	36.9	3.75 11.25	1/16 1/4		Note - butt and tip dimensions in ( ) are estimated. All weights
Do. No. 17	Do. 15.5 ft. in sand 1.5 in clay	(11)	(6)	36	0.21	1.15	10	2	13.1	39.3	9.0 27.5	1/16 1/4		of wood piles computed from dimensions - spruce 27 pounds/cu.ft - pine 40 pounds
Do. No. 26	Do. 11.8 ft in sand 1.9 in clay	(11)	(6)	30	0.17	1.15	10.5	2	14.3	42.9	11.5 28	1/16 1/4		Weights of Simplex and Raymond piles from makers data
Do. No. 29	Do. 10 ft in sand 0.5 in clay	(11)	(6)	30	0.17	1.15	6.5	5/8	23.6	70	9 20	1/16 1/4		
M.I.T. Group C No. 14a-5-8	Do. 11.5 ft. in sand 7.2 in clay	(10)	5	36	0.17	1.3	10	3 3/4	8.7	26.1	13.1 33.3 36.5 38.7	1/8 5/32 7/32 29/32		
Do. No. 2a-4-8	Do. 13.2 ft. in sand 0.5 in clay	(11)	6	30	0.17	1.08	10	2 1/2	10.4	31.2	7.0 9.3 12.3 14.9	1/32 7/32 1/4 17/64		
Do. No. 12d-6-8	Do. 11.5 ft. in sand 15.3 in clay	(12)	6	42.5	0.28	1.3	10	3	9.9	29.7	7.2 13.6 35.3 37.6 45	0.06 0.09 0.19 0.25 0.44		
Do. No. 2a-2a-8	Do. 12.5 ft. in sand 6.2 in clay	(11)	5 1/2	36	0.2	1.08	10	2	12.3	36.9	6.9 14.1 23.0 31.2	0.05 0.08 0.3 0.3		
Do. No. 12g-12-6	Do. 1.5 ft. in sand 18.5 in clay	(12)	5	45	0.28	1.3	10	3 3/8	8.8	26.4	15.9 26.9 32.0 36.8 41.8	0.06 0.19 0.25 0.31 0.62		
Do. No. 11a-6-4	Do. 0.0 ft. in sand 21.5 in clay	(12)	5	50	0.32	1.3	10	4 3/4	6.2	18.6	15.3 20.9 30.7 37.3 38.7	0.12 0.19 0.56 0.62 1.12		Pile tilted
Do. No. 10a-18-15	Do. 0.0 ft. in sand 23 in clay	(12)	5 1/2	42.5	0.27	1.15	10	3	8.6	25.8	6.0 10.7 18.2 20.5 30.0	0.02 0.03 0.12 0.25 0.37		
Do. No. 13g-13-7	Do. 5.8 ft. in sand 0 in clay	(10)	6	15	0.08	1.15	10	2 1/8	14.2	42.6	5.9 13.2 16.2 21.5	0.03 0.16 0.31 0.38		
Do. No. 11d-2-7	Do. 56 ft. in sand 0 in clay	(10)	5 1/2	15.5	0.07	1.15	10	1 5/8	18.3	54.9	8.3 13.4 21.4 26.9 32.2	0.05 0.16 0.44 0.75 0.82		
Do. No. n8-41-17	Pine, Drop Hammer 5.5 ft in sand 20.7 in clay	(13)	6 1/2	46	0.46	1.28	10	2	12.5	37.5	11.9 17.3 26.9 35.1 42.4	0.09 0.16 0.25 0.31 0.81		Pile failed by buckling
Do. No. 1	Raymond Concrete No. 1 Vulcan Hammer 10.2 ft in sand & grav.		8	23.2	4.8	2.5	2.25	0.2	21.4	64.3	23.0 45.4 62.7 72.3 91.2	0.06 0.12 0.18 0.25 0.4		Total length not recorded. Length tabulated is embedded length. - tabulated weight for striking parts only
Do. No. 2	Do. 6.4 ft. in sand and gravel		8	17.5	4.8	2.5	2.25	0.25	18.1	54.3	22.2 29.7 61.1 66.8 88.0	0.06 0.12 0.25 0.37 0.64		See above
Do. No. 4	Simplex Concrete Drop Hammer 4.0 ft. in sand & grav.		16	12.4	1.3	1.65	12	0.25	88	264	30.6 46.0 76.9 88.5 96.1	0.12 0.19 0.25 0.28 0.44		See above as to length
Melrose, Mass. U.S.A No. 1	Raymond Stub No. 1 Vulcan Hammer 3 ft. peat 10 ft sand gravel				4.8	2.5	2.25	0.2	40	120	30 30 40 50 60	0 0.1 0 0 0		
Do. No. 2	Do. 9 ft. in peat 10 ft. sand & gravel				4.8	2.5	2.25	0.25	30	90	30 40 60	0.06 0.16 0.31		
Do. No. 3	Do. 13 ft. in peat 11 ft. sand & gravel				4.8	2.5	2.25	0.33	24	72	30 40 50 60	0.16 0.28 0.31 0.34		
Do. No. 4	Do. 15 ft. in peat 12 ft sand & gravel				4.8	2.5	2.25	0.3	22	66	30 40 50 60	0.18 0.28 0.38 0.56		
Do. No. 5	Do. 19 ft. in peat 10 ft. sand & gravel				4.8	2.5	2.25	0.25	30	90	30 40 50 60	0.18 0.28 0.44 0.63		

assuming n = 0 $$R_d = \frac{eW(h - h_o)}{s} \times \frac{W}{W + P} \qquad (14)$$

Substituting the values for "e", and assuming a factor of safety of 3,

$$R = \frac{0.25\ W\ (h - h_o)}{s} \times \frac{W}{W + P} \quad \text{drop hammer} \qquad (15)$$

$$R = \frac{0.3W\ (h - h_o)}{s} \times \frac{W}{W + P} \quad \text{steam hammer single acting} \qquad (16)$$

Measuring drop of hammer in feet and penetration of pile in inches.

$$R = \frac{3W\ (h - h_o)}{s} \times \frac{W}{W + P} \quad \text{drop hammer} \qquad (17)$$

$$R = \frac{3.6\ W(h - ho)}{s} \times \frac{W}{W + P} \quad \text{steam hammer single acting} \qquad (18)$$

The values of all the terms in (17) and (18) are known except h_o.

The equation for h_o is a linear function for any given resistance, and the value of h_o may be readily determined experimentally in the field. Measuring the penetration for several blows at three different heights of drop and plotting the penetration as abscissae, the drop as ordinates, and drawing a line through them, the intersection with the Y-axis gives the value of h_o. If the points do not lie in a straight line there has been a change of resistance and the test should be repeated. Note that the value of h_o varies with the weight of striking parts of the hammer, the type, weight, area and length of pile, so that h_o should be determined whenever there is a marked change in these factors. Note, also, that h_o varies with the square of the dynamic resistance and so should be determined when near ultimate penetration or probable desired resistance. The value of h_o was determined in driving concrete piles at Boulogne s/Mer, France. The piles were about 16 inches square and 40 feet long. A square driving cap of azobe was used, the driving being done with a manually operated steam hammer, the striking parts of which weighed 7 metric tons and dropped 30 centimeters. The value in this case for h_o was 15 centimeters.

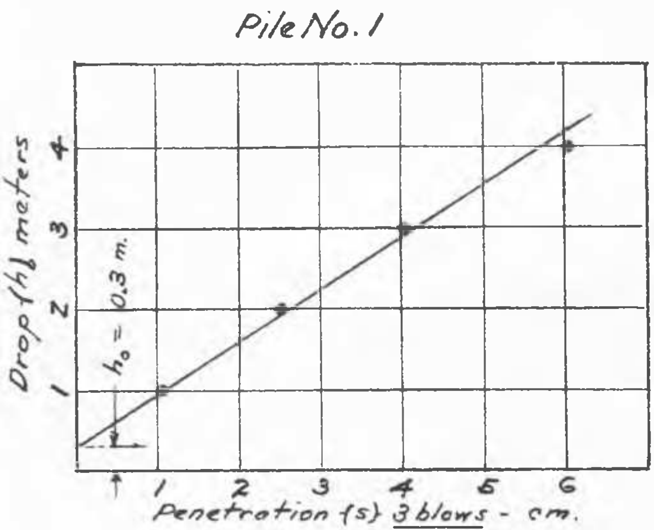
Formula (17) was used to verify the bearing capacity of piles driven for the foundation of the railway dry dock at Boulogne s/Mer, France, constructed in 1933. The piles were all of greenheart and were driven into sand and gravel, using a drop hammer weighing 1400 kilograms. Fig. 1, 2, 3, and 4 show the results of the determinations of h_o for the following piles.

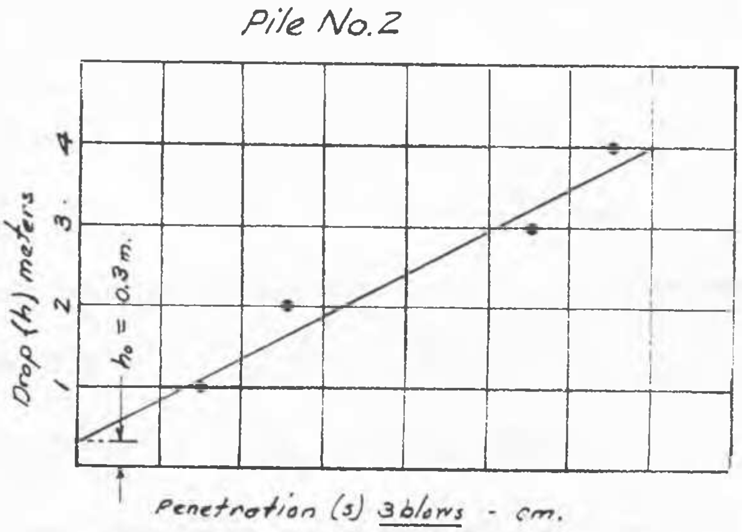
Pile No.	Length in meters	Diameter of butt in centimeters	Approximate weight in kilograms
1	10.80	40	1250
2	10.80	40	1250
3	9.10	30	640
4	10.70	40	1200

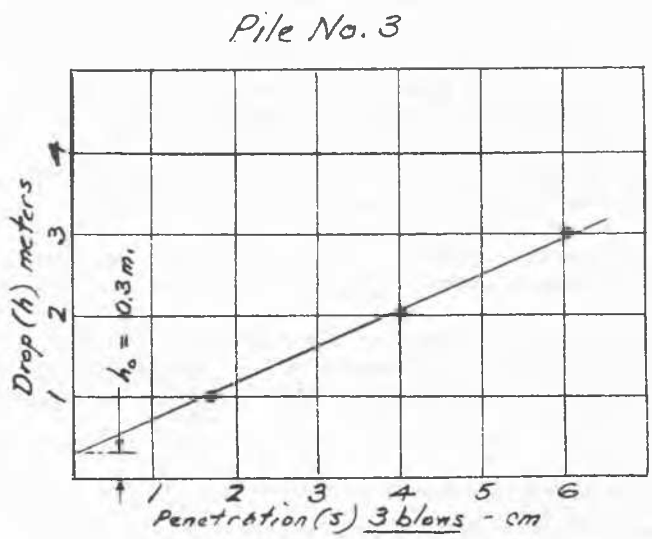
<u>Driving Results</u>

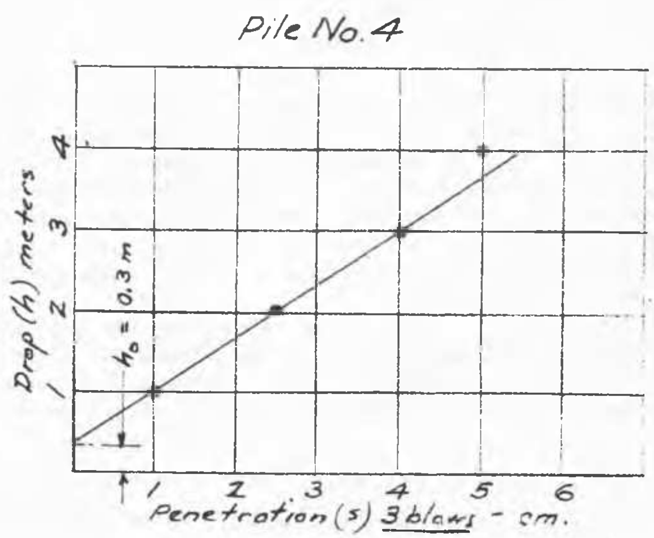
Penetration for 3 blows in centimeters

Drop	1.0	2.0	3.0	4.0
Pile No. 1	1.0	2.5	4.0	6.0
" " 2	1.5	2.5	4.5	6.5
" " 3	1.7	4.0	6.0	---
" " 4	1.0	2.5	4.0	5.0









The determination of h has the very great advantage of permitting the derivation of the real values of k. Equating (3) to (14)

$$k = \frac{h_o s}{h - h_o} \tag{19}$$

in which case k will include the values of all the deformations C, C_1, and C_2. This permits a verification and correction of the theoretical values and also permits assigning a reasonable value for C_2. In the case of the Boulogne tests above, the determination of k by formula (9) gives 0.12 in (3.0 m/m), while its determination by formula (19) gives 0.07 in (1.75 m/m).