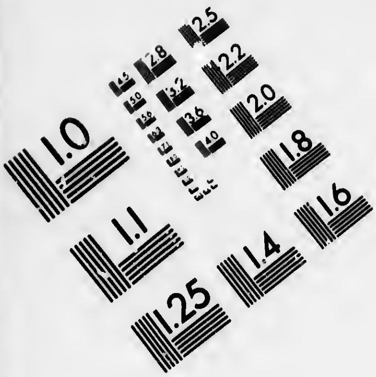

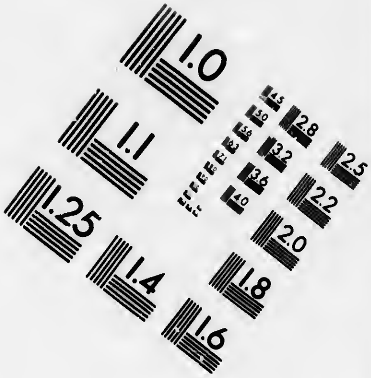

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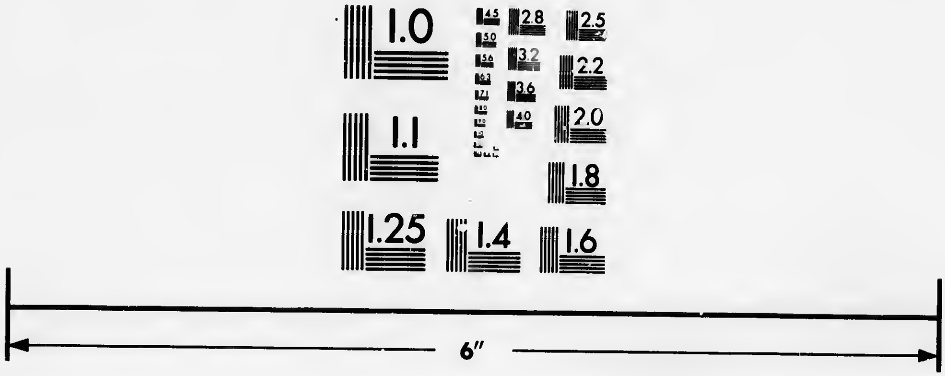

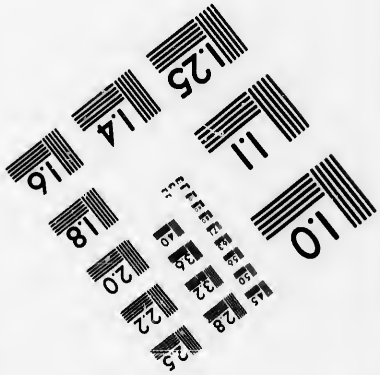

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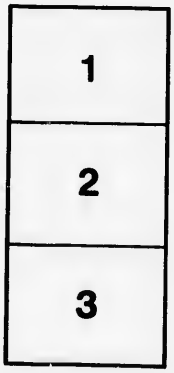

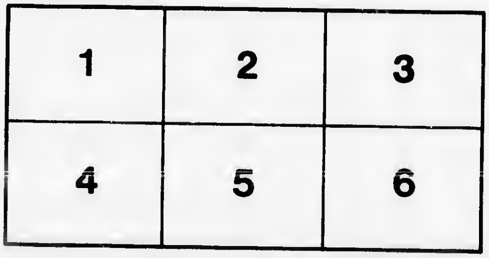

Canadian Society of Civil Engineers.
INCORPORATED 1887.
TRANSACTIONS.

THE RESISTANCE OF PILES.

By Henry F. Perley, M.Can.Soc.C.E.

Piles are used under varying circumstances:—(1) to form a foundation where the soil is of such a nature as to preclude the super-imposing of a structure on it, but which, by the use of piles, is compacted to such an extent as to afford sufficient resistance to a sinking or settlement of the piles which carry the load; (2) as a ready means of obtaining a foundation where a loose or soft stratum overlies a firm and compact material, to or into which the piles are driven and derive their support; (3) to serve as columns of support, as in the case when driven in clusters, or singly, as in pile-bridging and wharfing, where the piles are capped and carry only the superstructure, and a dead or a live load, but are subjected, it may be, to the lifting power or action of ice; (4) where they are driven to form a coffer-dam, and are not subjected to any vertical pressure, their object being to provide a water-tight structure, strong enough to resist the unequal side pressures to which they may be subjected; and (5) to form a retaining or revetment wall.

The resistance to which a pile is subjected is of a two-fold nature,—(1) that which it meets with whilst being driven, and (2) that which it offers in sustaining either a vertical load or a lateral pressure.

In the literature on "pile-driving," the subject appears to be treated in a very profound manner, and we have no end of wonderful calculations and still more wonderful formulæ to perplex the brain of the practical man, and needlessly worry him with their purely theoretical assumptions, complex forms, and variable constants; and all the more so, seeing that the formula which might apply in one case would not apply at all to others, and thus the adoption of the majority of the formulæ to be found in pocket-books and manuals is to be deprecated.

With regard to the resistance a pile offers in sustaining a load, a complication ensues, as it may be so placed that *two* different resistances have to be borne by it. In a foundation pile, whose head is on a level with the surface of the ground, and thus is supported throughout its whole length, the resistance experienced in driving is, in some degree, a measure of the resistance to settlement, and a greater load per square inch can be imposed on it, because it is a column supported at all points in its length against flexure and rupture, both of which actions are modified and, it may be said, greatly modified by the nature of the ground or soil into which the pile is driven; for it stands to reason that a pile which has passed through a comparatively soft stratum, and then penetrated a hard stratum, cannot support the same load that it would were it driven into a stratum solid throughout. Then again—take the case of a pile in a bent of a pile-bridge. Here we have a pile which is to be drived x feet into the earth, and to stand y feet above its surface, unsupported, except in so far as it may be tied to other piles by walings, braces, or caps. The resistance of the y portion of the pile is its ability to support as a pillar or column the dead and live load imposed on it, and to transmit such pressure to the x portion, to be met by the resistance afforded by the ground or soil into which it is driven.

The resistance to the downward movement of a pile is (1) that which is opposed by the displacement of a mass or quantity of earth equivalent to the cubic contents of the driven portion of the pile; (2)

the frictional resistance which exists between the ground and the pile such resistance varying with the nature of the soil or ground, the depth driven, and the superficial area of the pile in contact with the earth; and (3) the ability of the pile to withstand crushing, rupture, or deformation of any kind whilst being driven, or at any time during its use.

Supposing a pile 12 inches square to be driven 15 feet into the ground, then there must have been 15 cubic feet of earth displaced, for which room can only be found by a partial rising of the surface, and by a compacting or a compression of the earth surrounding the pile. The superficial area of the portion driven is 60 square feet, and therefore each superficial foot of pile surface displaces $\frac{15}{60} = 0.25$ cubic foot, equal to a film of earth 12 inches square and 3 inches thick. The density or compactness of this film is dependent upon the character of the earth or ground into which the pile is driven, and no doubt the resistance to the downward movement of the pile during driving, and its stability afterwards, are due, to a greater or less extent, to the frictional resistance set up by this compressed film,—a resistance equal to the greatest load or weight which the pile would support up to the moment when a movement or settlement takes place, always assuming that the load is not greater than what would crush and destroy the pile.

There is a great difference between *a dynamic force* and *a static pressure*, the former being represented by a blow from a ram falling from a height, producing an effect in a minute portion of time; and the latter by a load, applied, it may be, gradually during a longer or shortened period, or in increments defined or undefined as to amount.

As an illustration, the following data is assumed:—

Weight of ram,	2000 lbs.
Fall of ram at last blow,	5 feet.
Set under last blow,	0.5 inch.
Length of pile driven in ground,	20 feet.
Dimensions of pile,	12 × 12 inches.

From these data the dynamical force, or the "energy" of the ram developed at the moment of impact, and imparted to the pile, will—using the well-known formula for energy, $\frac{WV^2}{2g}$ amount to 10,000 foot-pounds, or the amount which would sink the pile to a depth of *one foot* in a stratum offering a resistance of 10,000 lbs. to the descent of the pile in that distance. In the data assumed the pile was driven to a depth of 0.5 inch only, or, the resistance to the downward movement was so great that the energy developed was only sufficient to cause a "set" of 0.5 inch, under the last blow of the ram falling from a height of 5 feet; hence the actual amount of energy displayed becomes $\frac{10{,}000 \times 12}{0.5} =$ 240,000 foot-pounds. This amount has a two-fold signification, for it represents (1) the frictional resistance of the earth to the descent of the pile; and (2) the load which the pile will bear without settlement.

It is assumed that the pile has been driven to a depth of 20 feet, and further assuming, for the sake of simplicity, that the point of the pile does not support any portion of the load, then the area in contact with the earth will be $20 \times 1 \times 4 = 80$ superficial feet, then $240{,}000 \div 80 = 3000$ lbs., or the average resistance of the earth per square foot of the driven surface.

The area of the pile is 144 square inches; then $240{,}000 \div 144 = 1667$ lbs. per square inch, which is in excess of the weight, as a permanent load, to which the pile should be subjected. Assuming a factor of safety of 8, the load becomes 208 lbs. per square inch.

In 1849, Major Sanders, U. S. Engineer, deduced from his experiments at Fort Delaware, "that a pile will safely bear, without danger of a further subsidence, as many times the weight of the ram as the distance which the pile is sunk the last blow is contained in the distance through which the ram falls in making the last blow, divided by *eight*," .... or expressed as a formula,

$L = \frac{WH}{8d}$, when W is the weight of the ram, H the fall in inches, d the distance sunk by the last blow, and L the safe load.

Applying the assumed data to this formula, we have:

$$\frac{2000 \times (5 \times 12)}{8 \times 0.5} = 30{,}000 \text{ lbs.},$$

and if this amount be multiplied by 8, we get 240,000 lbs., or the amount derived from the calculation for energy.

During the driving of a pile, the earth surrounding it is in a state of motion or vibration, and if the blows of the ram follow in quick succession, as in the case of a steam pile-driver, the particles of earth are kept vibrating and the tendency to settle is prevented, and thus the pile may be driven deeper and more quickly than by the usual machine worked by hand power, by which the blows are rendered at comparatively long intervals. It is well known that a bolt can be driven more quickly into a hole smaller in diameter than itself in timber, when *two* hammers instead of *one* are used, because the fibres of the timber are prevented from "setting" or hugging the bolt by the rapid succession of blows to the same extent they would otherwise do. A heavy ram falling from a small height will do better and quicker work than a lighter ram falling from a greater height, and a greater number of blows per unit of time can be given; and besides this, the chances of brooming or crushing the head of the pile are reduced to a minimum, hence the successful use of the steam pile-driver.

In the construction of works for the extension of the dockyard at [*] Portsmouth, England, it was found that on the resumption of pile-driving after an interval of some hours, the "set" of the pile was invariably much less than that observed on the cessation of driving, the fall of the ram being the same; and this result was accounted for in a great measure by the fact, that during the process of driving, the ground was to a great extent disturbed, and the vibration of the pile caused the hole from the surface downward to be slightly enlarged, thus relieving the pile from the full frictional resistance. On the cessation of driving, the ground settles or expands, and thus grips the pile to such an extent as to materially increase the frictional resistance. To determine the amount of increased resistance accruing from quiescence, special observations were made on a number of piles, the driving of which had been completed before closing the work for the night. On the following morning *one* test blow was given, and the resulting "set" compared with that of the previous evening; and it was shown that 39 beech piles, which had an average "set" of 0.054 ft. on completion of driving, when tested the following morning, gave an average set of 0.0234 ft., showing an increased resistance of 2.3 to 1.0. Seventy-four fir piles, which had an average "set" of 0.0306 ft., gave, after an interval of 14 hours, an average "set" of 0.013 ft., or an increased resistance of 2.81 to 1.0. Using these "sets," the data previously given, and Major Sanders' rule, we have:

For beech	piles,	safe load	at night,	23,148 lbs.
do		do	in morning,	53,380 "
For fir	do	do	at night,	34,090 "
do	do	do	in morning,	90,154 "

An examination of these results shows the great amount of uncertainty connected with the determination of the safe load which should be imposed on a pile, for it may be either under or over-loaded, when the night or morning "set" is taken as the correct factor, and it is this action which renders all the formulæ for determining the resisting to a great extent hypothetical.

Besides the resistance to further downward movement due to the dead and live loads, a pile in some instances has to withstand in cold countries an upward or drawing movement due to the action of ice, by which, as in the case of pile-bridging or wharfing, it is encompassed.

In tidal rivers or harbours where the ice is in constant motion, a film or coating forms on the surface of piles against which the moving ice rubs, and therefore does not produce any injurious effects; but a different action takes place when piles have been driven in bodies of

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[*] Proceedings Inst. C. E., Vol. 64, p. 164.

still-water in which an increase in volume is caused by an influx of water, and consequently a rise in elevation ensues. In rivers and small lakes, where their volume is augmented by the melting of snow, etc., the ice surrounding and adhering to a pile acts as a platform which is raised by the influx of water; and if the lifting power displayed is greater than the resisting power of the pile to withdrawal, then an upward movement must take place; but where the pile has an excess of resistance, the ice fractures and breaks away without causing damage.

Ice, we know, is water in its solid form, and we also know that its specific gravity is less than that of water, or as 0.9175 to 1.0;—or, in other words, a cubic foot of ice weighs 57.33 lbs., as against 62.5 lbs. the (accepted) weight of a cubic foot of water; and the lifting power of ice under the influence of rising water is therefore 62.50—57.33 or 5.17 lbs. per superficial foot, *one foot* thick.

According to a paper by Mr. J. F. James, M. Inst. C. E.,* the adhesion of ice to timber is 29.43 lbs. per square inch. Trautwine states that the adhesion ranges from 30 to 40 lbs. per square inch.

There is not any doubt but that the power to draw a pile is much less than the power to drive it, especially in the case of a round pile, which is tapering, and when once started is free to be moved easily upwards.

Mr. James made a number of experiments on the "Force required to draw a pile," with what may be classed as rods, ranging from 1 inch to 2 inches square, 1 to 2 inches in diameter, and 3¼ by 1 inch in section; and from the results of 40 experiments he determined a co-efficient C to be 0.3285, or that the power required to draw is to the power required to drive as 0.3285 to 1. Thus, in experiment 17, a pile 1¼ inches square was driven by a ram weighing 22.5 lbs., falling 7.2 feet at the last blow, the "set" being 0.895 inch, the driven length being 18.5 inches, and a force of 727 lbs. was exerted to draw it. Using Major Sanders' rule, omitting the factor 8, and the foregoing data, we have $\frac{22.5 \times (7.2 \times 12)}{0.895} = 2171$ lbs. as the resistance to downward movement. The force to withdraw was 727 lbs., and $\frac{727}{2171} =$ 0.335, which represents the co-efficient in this case.

In the removal in 1880 of the coffer-dam used in connection with the construction of the Albert Dock, Hull, England, in which piles were driven with a ram weighing 2240 lbs., falling on an average 5½ feet, the "set" at the last blow averaging 0.625 inch, and the driven length averaging 18¼ feet,—it was found that the average force to withdraw a pile was 75.869 lbs.

Now the "energy" developed, using the foregoing data, was 236,384 lbs. and $\frac{75,869}{236,384} = 0.321$ as the co-efficient in this case, which may be assumed agrees with those found by Mr. James.

Assuming a pile 12 inches square, and the adhesion of ice to timber at 30 lbs. per square inch, then the total force which can be exerted by ice one foot in thickness will be $(12 \times 4) \times 12 \times 30 = 17.280$ lbs., and the area of ice to be acted on by rising water to just move the pile will be $\frac{17.280}{5.17} = 3.342$ superficial feet, *one* foot thick; or the pile must stand isolated in the centre of a sheet of ice 58 feet square, which seldom obtains in practice.

The only satisfactory way of arriving at the load piles will carry with safety is to test the ground into which they are to be driven, by loading one—or more, which have been driven to what is considered a sufficient depth, with dead weight until settlement takes place, and from the results obtained to determine the final "set" for the remainder of the piles. Such a course is really only necessary where piles are classed as "bearing" piles, and not when they are used as "retaining" piles, as in a coffer-dam, etc., in which case it is only requisite that they be driven to a sufficient depth to ensure a water-tight enclo-

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* Proceedings Inst. C. E., Vol. 11, p. 191.

sure, and are large enough and strong enough to render the service expected from them.

Engineers, as a rule, when dealing with pile-driving, are too apt to follow a well trodden path by specifying hard and fast requirements, irrespective of the service a pile has to perform; and, in the opinion of the writer, full consideration of such service should be given before a specification is completed. In explanation of this, the following is offered: A masonry pier supporting the ends of two iron trusses of 150 feet span is to be built on a pile foundation comprising 60 piles, capped and covered with two tiers of timber 24 inches deep. Now, the dead load to be borne by 60 piles will be equal to the timber caps and flooring, the masonry pier, a proportionate part of the trusses and track; and the live load will be equal to that of the heaviest train which can be placed in one span, which though intermittent in its action must be provided for. Assuming the weight of the dead and the live load to amount to 1,800,000 lbs., the weight to be borne by each pile will be 30,000 lbs. Using *eight* as a factor of safety, the "energy" to be developed by the ram employed will be 240,000 foot-pounds. Using previous data as to the weight of ram and fall, it can easily be determined from Major Sanders' rule that a "set" of 0.5 in. will be required. Now, if it be specified that the piles shall be driven by a ram weighing 2000 lbs., falling from a height of 5 feet, until a "set" of 0.5 inch is obtained at the last blow, or is the average of a specified number of last blows, then reliance can be placed on the piles so driven.