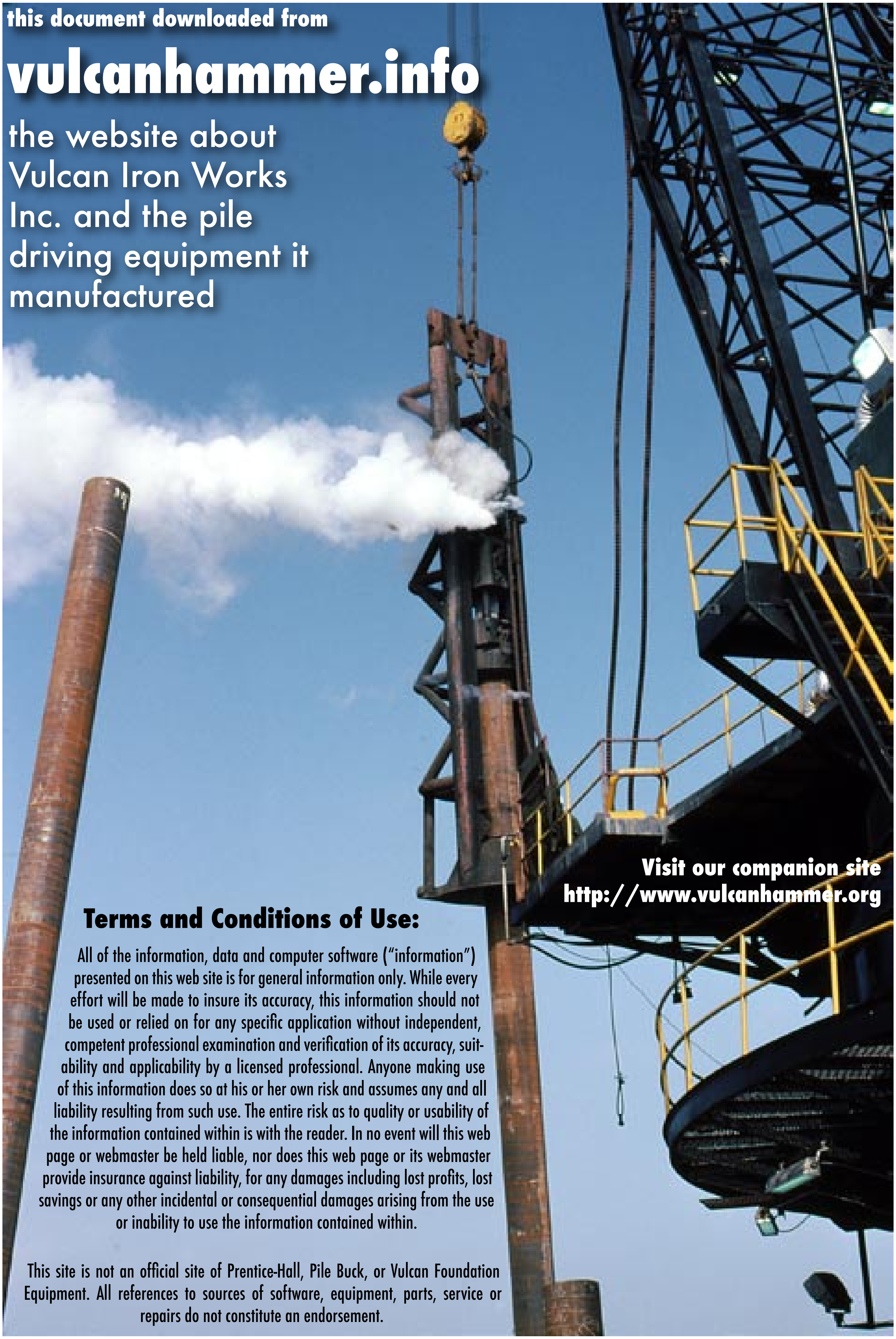

PILES

AND

PILE-DRIVING.

BEING A REPRINT OF SOME OF THE ARTICLES WHICH HAVE APPEARED IN ENGINEERING NEWS ON PILE-DRIVING AND THE SAFE LOAD OF PILES, AND OF THE PAMPHLET ON "BEARING PILES" BY RUDOLPH HERING, M. AM. SOC. C. E., M. INST. C. E.

EDITED BY A. M. WELLINGTON, M. AM. SOC. C. E., M. INST. C. E., M. AM. SOC. M. E.,
EDITOR ENGINEERING NEWS.

WITH COMPLETE INDEX.

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PREFACE.

The following work contains a reprint of some of the more important articles on the subject of "Bearing Piles," which have appeared from time to time in Engineering News, including especially those in which what has since become known as the "Engineering News Formula" for the safe load of piles was announced, explained and defended. It also includes a reprint of a valuable pamphlet on "Bearing Piles," by Rudolph Hering, M. Am. Soc. C. E., which was published some years ago by the Engineering News Publishing Co., but long since went out of print; and a full abstract of a paper by Mr. Foster Crowell before the American Society of Civil Engineers on "Uniform Practice in Pile Driving" with the discussions thereon.

It is believed that this little volume contains about all that can be required in any case for solving the most serious problem connected with pile-driving, what load can be placed on given piles with safety; but if it be desired to find fuller information as to specific records, the back files of Engineering News, of the Transactions of the American Society of Civil Engineers and of the Proceedings, of the Institution of Civil Engineers should be consulted, as they all contain further information of value; though the more important information to be had from all these sources is given in substance in this volume.

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THE

SAFE LOAD FOR BEARING PILES.

CODE OF RULES FOR SAFE LOAD OF PILES.

(The following article, reprinted from Engineering News of Nov. 17, 1892, was intended to give a codified summary of the net results of all the information which follows, so as to make it a trustworthy set of rules for good practice in pile driving, and it is believed to do so.)

In our issue of Dec. 29, 1888,* we published an article on the subject of "Formulas for the Safe Load of Bearing Piles," in which a simple formula for the safe load of piles was proposed which has since met with wide and increasing acceptance; so that we might fairly say, perhaps, that it is now one of the most generally approved for practical use, if not the most approved among those who know of it. We claimed for it then that it would be found more trustworthy than any one of 16 different formulas which were given in it, quoted from Mr. Hering's admirable monogram on "Bearing Piles."* The experience and opinions of others have since confirmed our belief that this claim was well founded, and especially a recent paper by Mr. J. Fos-

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* Republished later in this volume.

ter Crowell* before the American Society of Civil Engineers and the valuable discussion which followed it.*

We do not propose now to enter upon any detailed discussion of this discussion; it would occupy too much space, and would only be repeating in other words what has been said with sufficient fulness, perhaps, in the discussions themselves. It will be obvious to every one who reads the discussions, however, that they have added certain facts to our knowledge of pile-driving, and suggested and collated still more facts or well founded opinions. What we now propose to do, therefore, is to combine and codify in the form of suggested "Rules of Practice for Pile Driving" all those facts which seem to us to be sufficiently well determined to be incorporated in such a code, adding in a following article certain explanatory notes and tabulations by way of comment. The following is our suggested code of

RULES OF PRACTICE FOR PILE-DRIVING AND SAFE LOAD OF PILES.

A: METHODS OF DRIVING PILES.

Six methods of driving piles are in established use, which in order of frequency of use are as follows:

1. By the ordinary pile driving, in which a hammer weighing 2,000 to 3,000 lbs. or more is dropped 20 to 30 ft. or more, falling free, with an interval of several seconds (5 to 20) between blows.

* This paper and the following discussions, which contain a great deal of interesting and valuable information about pile-driving, is republished in abstract later in this volume, but will be found in full in Trans. Am. Soc. C. E., Vol. XXVII. (1892), p. 99-172 and p. 590.

2. The same as 1, with the important exceptions that (a) the hammer does not fall free, but is retarded by the rope and revolving drum, and (b) the blows succeed each other somewhat more quickly. (This method is an uncertain and often deliberately deceptive one, but properly used is legitimate as well as convenient.)

3. By the water jet, in which a stream of water under pressure is ejected at or near to the point of a pile and rises thence along its sides, removing most of the side and end resistance, so that the pile sinks rapidly by its own weight, with or without some extra pressure added. This method is suitable only for sandy or other fine soil, but in such soils is often very efficacious when no other is possible.

4. By direct pressure of an insistant weight. This method is applicable only to very wet soils (practically saturated with water) of a muddy or very fine silty nature, but in such soils is often the only effective way of driving.

5. By the Nasmyth or other like steam piledriver, in which somewhat heavier hammers (usually 3,000 to 5,000 lbs.) falling through much shorter falls (usually about 3 ft.) strike very much quicker blows (usually more than 60 per minute), but otherwise the same in principle as Method 1.

6. By gunpowder pile drivers, in which each blow is a double one, the first caused by the fall of the hammer after the last explosion, and the second (following close upon the first, so that there is no intermission in the movement of the pile, but still distinct), by the reaction of the explosion which throws the hammer upward.

B. BEARING POWER OF PILES DRIVEN BY METHOD 1.—ORDINARY PILE-DRIVING.

7. The maximum or ultimate bearing power, which is a CERTAINLY UNSAFE load, in the sense that experience shows that piles will rarely bear this load (or any close approach to it), for and length of time without settling, is given by the formula:

$$M = \frac{12\ wh}{s + 1}$$ in which

M = the maximum or ultimate bearing power by any unit of weight.
w = the weight of hammer in the same unit.
h = the fall of hammer in feet, as below defined and limited.
s = the set of pile under last blow in inches, as below defined and limited, and
1 = a constant which is made necessary by the fact that there is an extra initial resistance in getting a pile under way, and is intended to give the nearest feasible equivalent for the effect of that extra resistance in modifying the mean resistance to penetration. With individual piles it may or may not be a little more or less.

8. The safe or working load for piles, i. e., the load which it is CERTAINLY SAFE to place upon a pile under all conditions, except as below defined and limited, is shown by experience to be not over one-sixth of the above ultimate load, i. e.:

$$\text{Safe load} = \frac{2\ wh}{s + 1} = \frac{M}{6}$$

in which the symbols have the same values as in the prior formula, the application of both of them being subject to the following limiting conditions:

9. As to w: The effective weight of the hammer is decreased about 1% by wind resistance, and perhaps ½% by guide friction, even when the guides are truly vertical and in good order. When pile and guides are inclined the effective weight is decreased (1) to h cos. I (in which I=

the angle of inclination from the vertical) and (2) by the guide friction caused by the force w sin I pressing the hammer against the guides. With vertical guides this force is theoretically zero.

10. As to h: The full fall must only be counted (1) when there is no sensible bounce after the blow, and (2) when the head of the pile is in good condition. Bouncing in effect divides a single blow into two weaker ones, the energy of the first blow being diminished by an amount of fall equal to the height of the bounce, even if pile and hammer be assumed to be perfectly elastic. As neither is perfectly elastic, at least twice the height of the bounce should be deducted from h to determine its true value for use in the formula.

11. Condition of the head: According to the best existing information a broomed head will destroy from half to three-quarters of the effect of a blow, even if the brooming be only a half-inch to an inch deep. No formula can be safely applied if the last blows be given with the head in such condition; but the remedy is to adze off or saw off the heads before giving the last blows, at least for a few sample piles, and if a very considerable difference is observed, then for all of them, if it is desired to determine and utilize their full bearing power.

12. As to s: The proper value can only be determined by taking the mean of the sets for a number of blows, nor then unless:

(a). The penetration has been at a reasonably uniform or uniformly decreasing rate, and

(b). There is reasonable assurance that the penetration would continue uniform if driven several feet further (which may be known from test piles driven to an extra depth or from general knowledge or evidence as to the nature of the soil, as that it is all sand, gravel or alluvial deposit). Also—

(c). The head must be in good condition as per par. 11; and also:

(d). The penetration must be at a reasonably quick as well as uniform rate, not less than ¼-in. for a 3,000-lb. hammer falling 30ft. Any smaller penetrations under such a blow should be assumed to be due to mashing of the point and neglected, and any penetration of less than ½-in. is to be looked on with grave suspicion, and disregarded unless it has been uniform for many blows. With soft wood piles any penetrations of less than 1 in. under such a blow is likely to involve destructive strains within the pile, as per par. 14, 15, below, and hence should be disregarded in computing bearing power.

13. As to interval of time between blows: There is nearly always an increase of resistance and decrease of set per blow as an effect of an interval of rest, permitting the earth to settle firmly around the pile. The increase of resistance from a few minutes' to a few hours' rest may vary from 50% to several hundred or even thousand per cent. This effect is usually most pronounced in the finer, soft and wet earths, and least pronounced in coarse gravel and sand. No values of s should therefore be accepted as trustworthy without testing occasional piles for various intervals of rest, and the mean penetration for the first few blows after such an interval of rest should be taken as the value of s.

14. As to piles acting as columns. Assuming a blow of 3,000×20=60,000 ft.-lbs., a pile which penetrates through soft material to a comparatively hard stratum is not, as a rule, safe as a column (with a factor of safety of 6) for any heavier load than is given by the safe load formula of par. 8. That is to say for a set of

1 ins.	2 ins.	3 ins.	4 ins.	5 ins.	6 ins.

the safe load in pounds by par. 8 is

60,000	40,000	30,000	24,000	20,000	17,140

which is about 1-6 of the ultimate breaking load of a 10-in. round column of soft wood, of a height of

8 ft.	14 ft.	18 ft.	21 ft.	24 ft.	26 ft.

In cases where the length of column without side support is greater than this or the safe load by par. 8 is less, the safe load by the latter formula will exceed the safe load on the pile as a column.

15. Crushing strength. No pile can be relied on to bear without crushing over 500 to 1,000 lbs. per sq. in., unless of superior hard wood timber; or 50,000 to 100,000 lbs. in all, assuming the average section of pile to be 100 sq. ins. This is the safe load by par. 8 for a pile settling 1.4 to 0.2 ins. under a 20 ft. blow from a 3,000-lb. hammer. Therefore, penetrations of soft wood piles of less than 1½ ins. under such a blow (or proportionately for weaker blows) are to be looked on with some suspicion on this account, and penetrations of less than ½ to ¼ in. are to be disregarded wholly in computing bearing power, and s taken as =0.5 to 0.25.

16. Uplifting. Piles driven very close together in certain quicksandy or semi-fluid soils will sometimes rise somewhat when other piles are subse-

quently driven near them. While the precaution of giving them a few extra settling blows is expedient when time permits, they may be left as they are without much anxiety in most cases, as the phenomenon implies that the lower material is already solidly in contact with the pile, giving as great bearing power as the nature of the soil permits, after the soil has settled solidly about them. It is desirable to avoid this effect if possible, however, which can generally be done by driving the piles butt end down.

17. Bearing piles should be spaced at least 3 ft. c. to c. each way if this gives a sufficient number to carry the load, and they are worse than wasted if driven less than 2 to 2½ ft. c. to c.

18. Variations of load for varying conditions. No experimental evidence exists that par. 8 does not give a safe load under all conditions of service, within the limits of usual values for w, h and s. The load, therefore, need never be made less than par. 8 permits unless for some special case of treacherous or dubious soil under an important structure subject to vibratory strains. An extra allowance, if made, should ordinarily be made by reducing the spacing between piles, down to a limit of 2½ ft. c. to c. On the other hand, the load should only be made greater than warranted by par. 8 with extreme caution, under favorable conditions for high bearing power only, and with care that pars. 14 and 15 be not infringed.

19. Computation of Loads: All extra loads which may result from winds, locomotive counter-weight strains or other temporary loadings are to be considered in computing the load on

each pile. In pile trestles, it is none too great an allowance to assume that the entire weight of the driving wheel base falls upon each bent in succession.

C. BEARING POWER OF PILES DRIVEN BY METHOD 2.

(Hammer attached to hoisting rope.)

20. When the weight of the hammer has not only to set the hammer in motion but also the hoisting rope and drum, the energy of the blow ($= w\ h$) is in inverse ratio to the time taken for the hammer to fall a given distance free or attached to the rope, which may be observed experimentally or computed, assuming the mass of the drum to be concentrated at its radius of gyration from the centre. It will usually be found to be diminished nearly one-half, which requires a corresponding reduction in the value of h, that variable being supposed to equal the height of free fall.

(Deception is often resorted to in contract work under this method of pile driving; the fall of the hammer being checked by the brake in a way which it is difficult to guard against by inspection. It is therefore a method to be avoided in contract work.)

D. BEARING POWER OF PILES DRIVEN BY METHOD 3.

(Water jet.)

21. As a rule, the soils in which the water jet works to most advantage are those in which the hammer method cannot be used at all; i. e. in which the penetration will be little or nothing under any blows which the piles will sustain without crushing. If so, the loads which the

piles will sustain are limited only by their crushing strength or strength as a column, pars. 14, 15; or the same as if driven by hammer with equally small penetrations. In important cases where there appears room for doubt, the piles should be tested either by loading or (preferably) by a few blows of a hammer after the material has had due chance to settle firmly about them. In fine river or sea sands, however, it is certain that the penetration would be very small under hammer blows, and hence the bearing power will always be high.

E. BEARING POWER OF PILES DRIVEN BY METHOD 4.

(Dead load.)

22. As a rule piles sunk only by a dead load placed on them will not sustain safely much more than the load which sunk them, but will do that (and sometimes much more) after they have stood for a time, to let the material settle closely upon them. In very soft and semi-fluid muds, the safe bearing power may be sometimes the weight which originally sunk them. The only certain test is to try some of the piles with a hammer after they have been driven some time and then compute the bearing power by par. 8.

F. BEARING POWER OF PILES DRIVEN BY METHOD 5.

(Steam pile drivers.)

23. As a rule, the interval of time between blows is not more than 1-10 to 1-20 as great as in ordinary pile driving, and the velocity of impact not over 1-3 as great. Therefore, the constant 1 in the formula of par. 8, which represents the extra initial resistance of getting the pile in mo-

tion again should not be over 1-10 as great, if so much. Calling it 0.1 for safety we have for the case of steam pile-driver piles:

$$\text{Safe load} = \frac{2\,wh}{s + 0.1}$$

The same results will be reached if we retain the formula of par. 8, but let h = the total fall in feet in 10 blows. The formula as thus modified is at least not likely to give excessive loads in either case. If anything it is somewhat too conservative. There is a lack of experimental data on which to base any closer estimate.

G. BEARING POWER OF PILES DRIVEN BY METHOD 6.

(Gunpowder pile drivers.)

The gunpowder pile-driver strikes nearly as quick blows with a considerably greater average fall than by Method 5, par. 23. Moreover, only half of the effect of each blow is due to the fall of the hammer; the other half is due to the resulting explosion which throws up the hammer for the next blow. Otherwise, the conditions are substantially the same as by par. 23. Hence for the safe load of piles thus driven we should have

$$\text{Safe load} = \frac{2\,wh \times 2}{S + 0.1} = \frac{4\,wh}{S + 0.1}$$

This formula is also likely to err on the safe side, if at all; but experimental proof of safety should be required before it is exceeded.

DISCUSSION OF THE PRECEDING PROPOSED PILE DRIVING RULES.

Sir: In response to your invitation to discuss your "Suggested Code of Rules of Practice for Pile Driving and Safe Load of Piles" (Eng. News, Nov. 17, 1892), I ought, perhaps, simply to refer you to my discussion of Mr. Crowell's recent paper, in which I noticed at considerable length some of the points of which you now treat. I may, however, be permitted to repeat what I then intimated, viz., that "the elements attending the operation of the principles involved are so uncertain and so numerous, and the experimental data at hand are so uncertain and so few," that all rules upon the subject should (as my father observed of his own formula) be used with caution, and with a wide margin for safety in important cases.

Hence it seems to me a little hazardous to assert that the load given by your formula in par. 8 is "certainly safe under all conditions, except as below defined and limited," and that there is no experimental evidence to the contrary. The little collection of experimental data, which I submitted in discussing Mr. Crowell's paper, is vastly more complete than any other that I could find, and, in fact, embraces all such; yet these data are so few, so conflicting, and, in many cases, so uncertain, that I feel it would be quite within bounds to assert that there is no experimental evidence sufficient to confirm or to refute any formula. As you will see, your formula, in its approximation to the results quoted, compares favorably with the other two formulas then considered, yet we find that three of the four piles at Perth Amboy (my "case 4") settled with about 44,800 lbs. each. By your rule the safe load was 28,300 lbs. each. If these piles had been intended to support a wharf for the storage of grain, this would perhaps have been a sufficient margin of safety; but if they had been designed for a railroad trestle or for a tall factory with taller chimneys, and filled with rapidly running machinery and hundreds of operatives, a wider margin would have been desirable.

2. This, at least, emphasizes the criticism I have already made, that your formula in paragraph 8 is defective in that the factor of safety is made a fixed, not a variable, quantity. The second case given under Dordrecht (case 9) shows a nearly similar relation between the actual extreme load and the safe load as given by your formula. In other cases the safe load by the formula was greater than the actual extreme load, but the conditions of these cases were such that you would hardly consider them as coming within your limitations.

3. Under paragraph 10, I am disposed to ask: If the height of rebound must be deducted from that of the first fall, should not the fall from the rebound be taken into account, and its height be again added, restoring the height of fall to its original value, as though no "bounce" had occurred?

4. Under paragraph 23, I do not find it explained why we should assume that with one-tenth as great an interval between blows the initial resistance to driving "should not be over one-tenth as great, if so much." Indeed, referring again to my list of experimental data, I find that in the only two cases which we are, perhaps, warranted in taking as cases of steam-hammer driving, your formula, with divisor = s + 1, as originally given comes much nearer to the experimental results than it does with the divisor, made = s + 0.1, as suggested in this paragraph. Thus, at Brooklyn (case 8) the extreme load was 224,000 lbs., and your formula for extreme load (with divisor = s + 1) gave 242,000 or 202,000, according to whether we take the penetration at 0 or 0.2 in., an exceedingly close agreement for pile driving data. But if we make the divisor s + 0.1, your formula gives extreme load 242,000 and 806,400 lbs. respectively. For Dordrecht (case 9) we have (or believe we have—see p. 156 of discussion) actual extreme load 13,440 lbs.; extreme loads by your formula with divisor = s + 1, 48,120 lbs.; with divisor = s + 0.1, 139,300 lbs.

5. This consideration confirms me in questioning the soundness of the reasoning by which you seek to demonstrate the logical correctness of the constant addition of 1 (common to your formula, and to ours), in the divisor, for all cases of driving with ordinary machines; for, by that reasoning, the quantity to be

added to s ought, as you say, to be less for steam-hammer driving.

"Used with caution, and with a wide margin for safety," your code, I think, will serve a useful purpose; but I think, also, that, considering how much we don't know about the bearing power of piles, "presumably" is, "in all cases" connected with the subject, a better word to use than "certainly."

John C. Trautwine, Jr.

Philadelphia, Dec. 19, 1892.

(1. We are yet waiting for the first recorded instance where the formula proposed by us

$$\text{Safe load} = \frac{2\,w\,h}{s+1}$$

does not give a load which is "certainly safe" for a pile driver under conditions of good practice, or, indeed, under any conditions. There have been quite a number (chiefly of piles driven in mud) where a greater load would have been safe; none to the contrary. Opinions will differ as to what is "sufficient" to establish a formula. We consider that a formula shown theoretically to be consistent (i. e., rational) under all conditions, and shown practically to be inconsistent with no records, is amply established. The Perth Amboy record seems to us perfectly satisfactory. What better can be asked of a formula than to show a pile safe for 28,300 lbs., which actually fails under 44,800 lbs.? The assumption that this pile, which was safe for a wharf, might not have been safe under a factory is pure assumption.

2. There is no disputing about tastes. It is a weakness of our poor human nature to love to do its guessing under cover, so to speak; to like better to be told "here is a limit certainly unsafe; take such a slice as you, in your excellent judgment, may think best," instead of being told "this much is safe; you may sometimes go beyond it safely, but take a certain risk in doing so." Guesswork

has its place, but its place is not in a formula; and it should always be recognized for what it is.

3. Of course not. The second blow is a second and distinct one; usually ineffective because too weak.

4. It is bad testing formulas by single cases, especially where there is so much room for doubt as to the real facts of the case, as in those cited.

5. Argument on this point is exhausted. It was not alleged that in every case of practice some change in the constant might not come nearer to the truth for that particular pile, but only that these were of the nature of "errors of observation," liable to be either way, and that a constant should not be made a variable unless it could be varied intelligently and for specific reasons stated affecting that one constant and not the formula as a whole. If it is desired to make the formula variable, make it so directly by factoring the whole of it; and when it is nothing but guessing, make it a guess. Don't disguise it under a false pretence of precision, for the details of which no rational basis is claimed.—Ed.)

FORMULAS FOR SAFE LOADS OF BEARING PILES.

(From Engineering News of Dec. 29, 1888.)

We have received from Mr. John C. Trautwine, Jr., the following letter:

Sir: In your issue of Oct. 27, F. P. K. states that he has found that good white oak piles 30 ft. long by 12 ins. in least diameter, and driven by a 2,000-lb. hammer, are safe for railroad trestles if they show only

1	in.	penetration	under	14	ft. fall.
1¼	"	"	"	17	"
1⅛	"	"	"	20	"
1¾	"	"	"	23	"
2	"	"	"	26	"

and asks for data embracing other weights of hammer and other falls.

In the absence of fuller particulars I venture to refer F. P. K. to a former communication of mine in which I gave a number of experimental data in order to compare a formula suggested by Prof. Ira O. Baker, of Champaign, Ill., with the not very difficult empirical formula given in "Trautwine's Civil Engineer's Pocket Book," which is:

$$\text{Extreme load in tons of 2,240 lbs.} = \frac{\text{Weight of ram in lbs.} \sqrt[3]{\text{fall in feet}} \times .023}{\text{Last penetration in ins.} + 1}$$

$$\text{or extreme load in pounds.} = 51.52 \frac{\text{Weight of ram, in lbs.} \times \sqrt[3]{\text{fall in feet.}}}{\text{Last penetration in ins.} + 1.}$$

This formula, compared with the actual results, shows as follows:

	Wt. of ram, lbs.	Fall of ram, ft.	Penetration, ins.	Ultimate load— Actual lbs.	By our formula, lbs.
1. U. S. Govt. trial pile, Proctorsville, La.......	910	5	0.375	60,500	58,240
2. Phila'phia. 1873.	1,600	36	18.0	14,600	14,336
3. Brooklyn Navy Yard...........	2,240	30	0.5	224,000	239,200
4. Pensacola Navy Yard	2,200	30	0 5	91,800	235,000
5. Buffalo, N. Y...	1,900	29	1.5	{75,000 to 150,000}	120,000

Other experiments were given, but the foregoing were the only ones for which I am able to state the extreme load.

The formula appears to fail badly in case No. 4, but the actual extreme load in that case is so far below that in case No. 3 (where the conditions were almost identical) that it would seem justifiable to suppose that some special feature may have facilitated the failure of the pile. The pile was entirely in clean white sand, open and porous, 1 cu. ft. being capable of holding 6 qts. of water, and it would be easy to make a case for the formula by supposing a change in the matter of moisture after driving.

But this case strikingly illustrates the extent to which the unknowable enters into the matter of the bearing power of piles, especially where the ground is wet or liable to become so, and the inadvisability of pinning absolute faith to any formula, however simple, on the one hand, or however handicapped with weight of pile and modulus of elasticity of ram, pile and ground on the other.

Case 5 is a further illustration. Up to 75,000 lbs. there was no settlement; with 75,000 lbs. there was a settlement of ⅝ in., and there the pile stopped. With 100,000 lbs. there was a further settlement of ⅞ in. With 150,000 lbs., there was a further settlement of 1 9-16 ins.

Now what was the extreme load in this case? If it was 75,000 lbs., our formula (giving 120,000 lbs.) errs on the dangerous side. If it was 100,000 lbs., the formula is a little more than safe, while if we take the mean (say 108,000) of the three loads, the agreement is about as close as need be.

Can F. P. K. give us the extreme load on one of his trestle piles? If not, he can no doubt tell us how much they safely bear, and it must be borne in mind that they are subject to vibrations, which must exercise an important but incalculable effect especially in soft or wet ground.

Yours truly,

John C. Trautwine, Jr.

We think our correspondent's closing question in the next to last paragraph, is rather a bit of special pleading. The "extreme load" which a pile can be regarded as in any sense safely sustaining is that under which it first begins to settle by some appreciable amount, like ⅝ in. The fact that the pile then stopped has little to do with the matter; the next pile might settle 3 or 4 ins. and then stop; and in actual work, the settlement by any amount of any one pile among a number throws just so much more work on the rest, with increased probability that they will settle in turn.

The Trautwine formula, therefore, gave decidedly too great an extreme load in two out of these five cases, and the extraordinary difference in ultimate resistance of piles 3 and 4, driven under almost identically equal conditions, may well tend to throw discredit on all formulas, even as approximate guides. Again, although our correspondent F. P. K., as quoted above, gave 2 ins. as a safe minimum penetration for trestle piles under a 2,000-lb. hammer falling 26 ft., yet there are plenty of trestles in all parts of the country where the actual penetration was 3 or 4 ins. which yet stand very well. We are not now recommending such practice; we only say that it exists, and so far as we know has never caused an accident, and that in many places it would take a pretty long pile to get a much smaller penetration. By Mr. Trautwine's formula the ultimate load for such a pile would be 2-5 of one which penetrated 1 in. and 1-5 of one which did not penetrate at all, and its ultimate load would be 64,034 lbs., which seems not unreasonable and leaves a sufficient margin for the known loads (say 60,000 lbs.) placed on 4-pile bents to account for their standing, although likewise indicating that they are none too safe. With piles 3 ft. apart, a column of masonry about 40 ft. high would place this load upon it; yet we have certainly known masonry of nearly this height placed on piles driven to only 2 to 2½ ins. penetration with never a settlement resulting; and in the very case we have in mind, the last penetration varied between 1¼ and 2½ ins. in adjacent piles, which there is not the slightest real reason for believing had any great difference in ultimate bearing capacity, the material being exactly the same, a coarse gravel.

That pile-driving and pile loading must forever remain an empirical art, defying close analysis by formula, is indicated in another way by the enormous difference which the character of the blow and the condition of the top of the pile make in the penetration. In the mud of the Hudson River it is almost impossible to drive a pile by blows at all, and most of those which are driven are "pulled" down from a scow by placing part of the weight of the scow as an insistent weight on it, beneath which it gradually sinks. When the load is taken off, these piles remain solid under any load which does not approach too closely to that by which they were driven; but if originally driven by hammers, they cause no end of trouble by continuous slow settlement, and some of the ferry slips of Jersey City and Hoboken are only kept in place by arrangements for constant readjustment of the pile support, for which there are ingenious permanent arrangements.

How great a difference the condition of the head of the pile makes in the penetration under the last blow, and hence in the resisting power, is indicated strikingly in some figures given in a paper by Don. J. Whittemore,* showing the gain in penetration by cutting off the broomed end of a green Norway pine pile, driven by a 2,800-lb. Nasmyth hammer falling 36 ins., from which we abstract the following table, showing the number of blows required to cause each successive foot of penetration:

Ft. penetration.	No. of blows to drive 1 ft.	Ft. penetration.	No. of blows to drive 1 ft.
3	5	Head adzed off.	
4	15	15	275
5	20	16	572
6	29	17	832
7	35	18	825
8	46	Head adzed off.	
9	61	19	213
10	73	20	275
11	109	21	371
12	153	22	378
13	257		
14	684	Total No. of blows,	5,228

According to any one of the established formulas for pile-driving, the ultimate load which the pile would sustain would have been three or four times as much, had driving stopped just before adzing off, as if it had stopped just after; yet no reasonable man can doubt that its real resisting capacity was much less.

In order to show what various engineers have evolved from their inner consciousness as about the proper thing for piles, we give in the accompanying table a full abstract of all the leading

* Given in full later in this volume.

formulas from the simplest to the most complex abstracted from a valuable paper on the subject by Mr. Rudolph Hering which every engineer should have, published by us in 1887.* The last nine columns of the table we change from the form given by Mr. Hering to a form giving the relative resistance indicated for piles driven under varying conditions, taking as a unit the resistance of a pile driven by a 2,000-lb. hammer falling 30 ft. In al. cases the last penetration is taken as 0.1 ft. It is evident that the ratio of ultimate loads under various weights of hammer and falls is of more importance than the absolute amount; since there must be a certain factor of safety any way: and if the ratio of all formulas be the same, we shall obtain the same safe load from any one of them simply by varying the value of the coefficient F common to all the formulas.

As respects the effect of different hammer falls, taking 30 ft. fall in each case as unity, we have:

	2,000-lb. hammer.		1,000-lb. hammer.		500-lb. hammer.	
	10 ft. fall.	5 ft. fall.	10 ft. fall.	5 ft. fall.	10 ft. fall.	5 ft. fall.
Simpl'st f'rm'l'a	.333	.167	.333	.167	.333.	.167
Most complex....	.333 to .398	.159 to .208	.278 to .064	.140 to .232	.520 to .333	.260 to .064
Trautwine......	.695	.550	.695	.550	.695	.550

McAlpine's, Rondelet's and Rankin & Mason's formulas are neglected in this summary as not really intended to be general for all conditions. The simplest formula is the first one given in the large table.

$$F \frac{wh}{s}$$

Now, examining this table, is there the slightest evidence that the more complex formulas approach any more nearly to the true ratio of experience

* Given later in this volume.

than the simpler form, which gives the resistance as inversely to the fall, penetrations being equal? If there is, we fail to see it. These complex formulas dodge all around the simpler form, sometimes larger, sometimes smaller; with a tendency, however, toward the extreme embodied in Trautwine's formula, which differs markedly from all others of note in attaching little weight to height of fall. To a certain extent we know this to be justified. A 30 ft. fall will hardly triple the resisting power due to a 10 ft. fall, but will any one believe that a 10 ft. fall pile may properly be trusted with 70% of the load placed on a 30 ft. fall pile? The most rigorous theoretical analysis, as embodied in such formula as Redtenbacher's and Wiesbach's do not differ materially from the direct inverse ratio, and bearing in mind that the high falls are rather the unit from which we measure, and that the only effect of complexity is to increase the loads placed on small fall piles, we fail to see anything to be gained by it.

As respects the effect of weight of hammer, we have the following comparison, taking the 2,000-lb. hammer as unity, and other conditions as above:

	30 ft. falls		10 ft. falls		5 ft. falls	
	1,000-lb. hammer.	500-lb. hammer.	1,000-lb. hammer.	500-lb. hammer.	1,000-lb. hammer.	500-lb. hammer.
Simplest formula	.500	.250	.500	.250	.500	.250
Most complex....	.417 to .695	.157 to .307	.417 to .693	.417 to .693	.417 to .693	.417 to .693
Trautwine.........	.500	.250	.500	.250	.500	.250
Nystrom...........	.348	.098	.317	.098	.363	.102

Nystrom is given separately as very exceptional, and plainly inadmissible.

Here all the formulas agree in assigning the same ratio of effect to hammers of varying weights under varying falls; but is there any reason apparent why, the fall being constant, the effect of the blow should vary materially from being directly as the weight of the hammer? Plainly not to the theorists as a class, since they vary on each side of this. If anything the lighter hammer should have somewhat less than proportionate effect, yet the most of the complex formulas give the effect of the lighter hammers as somewhat greater than that of the heavier ones in proportion, apparently from purely mathematical reasoning: "If it does not conform with the facts, so much the worse for the facts." Within the moderate limits of variation which occur in practice, we see no evidence of any theoretical or practical gain by varying from the simple assumption that the resisting power varies directly as the weight of the hammer, all other things being equal.

The effect of the factor s (penetration under last blow) in the various formulas we have not analyzed, since Mr. Hering did not enable us to do so easily by computing a table of ultimate loads for various values of s. In most of the formulas L is inversely as s, which plainly cannot be correct, as when $s = 0$, L becomes infinitely great. To avoid this absurdity, Trautwine adds to s the constant 1 in., which seems to us the true principle. Others have extremely complex forms, the effect for which can only be determined by trial.

The form of equation which it seems to us, in view of the proceding and some following facts, is the proper and only one likely to be useful in practice is of the form:

$$\text{Safe load } L = F \frac{wh}{s + c}$$

in which $w =$ wt. of hammer $h =$ fall, $s =$ last penetration, $c =$ some constant addition to s, preferably 1 in., and $F =$ a constant determined from experience. This in the first place conforms closely to the theory of pile-driving. We distrust all formulas which, like Trautwine's cube root formula, are not only unsupported by, but in direct and complete antagonism to, theory. The hammer in falling stores in itself a certain force, which is the driving force, measured by wh. By this force the pile is moved a certain distance s, and barring the energy wasted in brooming the pile and heating pile and hammer, it is mathematically certain that the AVERAGE resistance against which the pile moves through s is measured by $\frac{wh}{s}$, from which it is a simple inference that the ultimate load shall be in some fairly close ratio thereto.

Such conclusion is modified by several theoretical and practical considerations, the first of which is that the resistance is very unequal at the beginning and end of the motion s, being increased at the beginning by the pile's inertia and decreased at the end by the pile's vis viva. It is on this account that heavy hammers with small falls are more effective than light hammers with high falls; the latter attempt to communicate too great and too sudden a velocity to the pile; and it is on this account that the weight, area and length of pile, modulus of elasticity and what not, enter into formulas seeking to be theoretically exact. The friction is also much greater at first than after the pile is started, and the rapidity of the blows has a great effect which defies analysis; quick blows being vastly more effective than slower ones, because leaving no time for the ground to settle and stiffen around the pile between the blows. This fact, however, tends to make the sustaining power greater than that exerted at the end of the last blow, and to compensate more or less for other sources of error.

If we assume that the ultimate load for a pile = average resistance during last blow, or $\frac{wh}{s}$ we have for a 30-ft. fall of a 2,000-lb. hammer, with $s = 0.1$ ft.

$$L' = \frac{30 \times 2{,}000}{0.1} = 600{,}000 \text{ lbs.}$$

as in the first (Sanders') equation of the table.

If we give this equation the form suggested above, making $c = 1$ in. or 0.0833 ft., as in Trautwine's formula, we have for ultimate load:

$$L' = \frac{30 \times 2{,}000}{0.1833} = 327{,}000 \text{ lbs.}$$

In the large table it will be seen that the more elaborate formulas differ much more from each other than they do from this, and comparing it with the observed ultimate load for five different piles as quoted in Mr. Trautwine's letter above, we have:

Pile No.	Actual ult. load, lbs.	$L' = \frac{wh}{s}$	Ratio, (actual=1).	$L' = \frac{wh}{s + 0.083}$	Ratio (actual= 1.0)
1	60,500	145,600	2.4	39,700	0.66
2	14,600	38,400	2.6	36,300	2.49
3	224,000	1,612,800	7.2	537,000	2.40
4	91,800	1,584,000	17.2	527,000	5.75
5	75,000	440,800	5.8	264,000	3.53

The observed load for pile 1, with a 910 lb. hammer falling 5 ft. and ⅜ in. penetration, is disproportionately great by either formula; but the extreme case of pile 2 with 18 in. penetration is much less anomalous in the last, which likewise seems to us to give better (because more uniform) results than Mr. Trautwine's formula. The average factor may be taken as somewhat under 4, and the indications from the above and many other facts seem to us decided that a factor of safety of 6 will cover adequately the weakest piles driven under fairly normal conditions, while not falling in any case sensibly below the loads warranted by good practice. Taking likewise the last penetration in inches instead of feet, this gives to the equation for safe load the simple form:

$$L = \frac{2\,wh}{s + 1}$$

Comparing this with the safe loads given by other formulas, most of them extremely complex, we have the following:

Safe Loads for Piles Sinking 0.1 ft. Under Various Blows, According to Various Authorities.

	30 ft. fall of 2,000-lb hammer.	5 ft. fall of 500 lb. hammer
Sanders	200,000 to 75,000	8,333 to 3,125
Mason	120,000	3.125
Trautwine	84 900 to 14,150	11,680 to 1 950
McAlpine	68,200	(negative)
Rankine & Mason	28,800	28,800
Rankine	262,600 to 52,180	11,416 to 2,483
Weisbach	45,265 to 4,526	2.467 to 267
Redtenbacher	98 810 to 65,870	3 101 to 2.070
Brix & Becker	96,000 to 64,000	6,250 to 4,167
Weisbach	48,250 to 4,825	1,350 to 136
Nystrom	64,000	1,010
Brix & Becker	24,000 to 16,000	1,562 to 1,042
By formula $L = \frac{2\,wh}{s+1}$	54,545	2,273

When such extreme variations are allowed as in some of these cases, a formula becomes worse than useless, as also with such excessive coefficients of safety as Weisbach's (0.1 to 0.01). There are no reasons why there should be any very great difference in factor for different soils; penetration, hammer and fall being the same. We question if under these conditions greater differences than about two to one ever have been or will be observed in however different soils, assuming always that the pile does penetrate and with some approximate regularity under the later blows. It appears to us therefore, and we suggest to the profession as a result of no little examination of the facts as to pile driving at various times, that there is no better nor safer formula than this for the safe working load for piles under all ordinary conditions, to be reduced under exceptional conditions (as notably with irregular penetration) but never exceeded unless the pile is known to rest on rock and act as a column:

$$L = \frac{2\,wh}{s+1}$$

in which L = the safe load in lbs.; W = wt. of hammer in lbs.; h = fall in ft., and s = penetration under last blow in inches, assumed to be sensible and at an approximately uniform rate.

If there are any facts on record tending to invalidate this formula, or to indicate that another would be better, we should be glad to know them. It is at least consistent, and cannot lead astray, as the miscellaneous assortment in our large table is very liable to do.

PILE DRIVING FACTORS OF SAFETY.

(From Engineering News of Aug. 6, 1889.)

It will be remembered that in our issue of Dec. 29, 1888, we discussed somewhat at length "Formulas for Safe Loads of Bearing Piles."

Several correspondents have written us since, expressing approval of this formula, including one much-respected correspondent whose letter we published March 16, Mr. John C. Trautwine, Jr., but who yet expressed a preference for the more complex form which is endorsed by Mr. Trautwine, Sr.'s high authority:

$$L = F \frac{50\,w\,\sqrt[3]{h}}{s + 1}$$

in which F = the factor of safety, w = weight of hammer in lbs., h = fall of hammer in ft., and s = set of pile under last blow in ins.

The pros and cons of the main question, raised by Mr. Trautwine's letter, we expressed our views on, March 16, in a note appended to his letter, and do not propose to again consider; but there was one argument advanced in his letter which we shall briefly consider, since it has a certain general bearing on other questions of the kind; illustrating likewise, from our point of view, certain weaknesses of human nature, which crop out curiously in such matters, sometimes harmlessly, and sometimes not so harmlessly.

Mr. Trautwine suggests that his formula above has a certain decided advantage from having in it the factor of safety, F, which can be "varied according to circumstances," whereas the result of the other formula is not so variable. He possibly carried with him the sympathy of many readers in his argument on this point, which we quote verbatim:

Nor can I think the use of a constant factor of safety an improvement, for it aims to fix one of the most unfixable factors of the case, giving, as I understand, the same factor of safety for a low brick shed, in ground free from vibrations or inundations, as for a lofty cathedral, with a tidal river at one side and the jar of railroad traffic on the other.

While our ignorance remains, we must use its factor; and the denser that ignorance, the greater must be both the factor itself and its range of variation. It seems to me, therefore, more scientific (or, what is really the same thing, more practical), to try to approximate to the "extreme" load, and leave the factor of safety to the judgment. The result is shabby, but I don't see that the case admits of anything better.

This argument has a plausible sound, and in its statement of facts is perfectly correct. The formula

$$L = \frac{2\,w\,h}{s + 1}$$

does give "the same factor of safety for a low brick storage shed, in ground free from vibrations or inundations, as for a lofty cathedral with a tidal river on one side and jar of railroad traffic on the other." It gives, and was intended to give, values perfectly safe for the worst case, leaving the piles under the "low brick storage shed" to have a certain excess of strength, unless the engineer chooses to presume on his favorable conditions to make a special case and advance beyond it.

Now what possible advantage is there in doing otherwise? What but the shadow of an atvantage, which is really an unmitigated disadvantage, is even promised by doing otherwise? Let us see what is the difference, and the only real difference between these two formulas.

The first formula says in effect: "Here is the load which any ordinary pile cannot resist. Some will carry only half, some a quarter, some a sixth or less (penetration, hammer and fall being always the same). Make your own guess—according to circumstances."

The second formula says in effect: "Here is the load that any ordinary pile (with given penetration, hammer and fall) is certain to resist. Some lucky ones may resist five or six times as much (of course, or it would not be a safe load), but any excess above this involves risk."

Now, is there any real difference between these two as regards applicability to varying conditions? There is one very real one, so far as we can see, and only one, viz.: That formula (1) enables a man to deceive himself with the notion that he is being cautious when he is really being rash, while formula (2) forces him first expressly to admit to himself that he is being rash. Hence formula (1) appeals to some of the deepest foibles of our human nature, for we all like to persuade ourselves that we are wiser and more cautious than we are. But the essential nature of the act is precisely the same when the engineer takes a certain maximum load which is never safe, and, on the strength of his own judgment only, says, "I will use a third of that load in this case, but only a sixth of it in that," as when he takes a formula which simply gives the universally safe load and says, "I will use this value in this case, where I want to be sure; but in that other case, which seems less important and to have better conditions, I will double the load;" hammer, fall and penetration being understood to be always the same.

Nay, if a man is going to vary in this way, according to circumstances, we maintain that he can do it more correctly and surely by increasing from a lower "always safe" value, than by decreasing from a higher "always unsafe" value; but is it really justifiable to do it at all, in pile-driving at least, and is there really the slightest justification or excuse to embody in a formula an invitation to do so? It is to be remembered that the piling is always planned before the precise nature of the soil is known, and that even after the piles are all driven we do not know it fully. No one in his senses reduces the number of piles that he had previously planned because he finds the indications as to soil a little better than he counted on. He may increase the number of piles under reverse conditions, but that is only because he either cannot get uniform penetration, or cannot get last penetrations as small as he expected. There remains therefore only the question of whether it is wise and proper to countenance in a formula loading piles under a "low brick storage shed" with twice the loads that piles driven by equal hammer blows to equal penetrations bear under a "lofty cathedral."

No one will dispute that, under some rough-and-ready temporary structure, it may be proper to pile on hap-hazard all the load the piles will carry, and let them settle or not as it happens; but if a "low storage shed" be built to stay, we see no reason why its 40 or 50 piles should be more heavily loaded than the 2,000 or 3,000 piles under a cathedral. Its ground "free from vibration" may next year have tracks on both sides of it. Its load is variable and may be highly vibratory, while the cathedral load is not. Its soil just below the piles may be far worse than suspected. A failure of a single pile cracks and perhaps destroys it. Does it pay to take these chances simply because the building is unimportant, if it is intended to be permanent?

When, as in bridge designing, the necessity for a varying factor arises from known and in a sense measurable differences of conditions, as in floor-hangers, and main members, then there is reason and excuse for varying factors; but when the causes for actual variation are wholly unknown and unforeseeable, as among a hundred piles driven to exactly the same penetrations by similar and equal blows, we see no reason for taking further chances with any kind of permanent structure, to save so cheap an article as piles. For every structure the load should be that load under which no one of a hundred or a thousand such piles will fail, and not half or quarter or sixth of that under which they may be expected all to fail. "Factors of ignorance" must remain numerous enough at best; there is no excuse for encouraging or perpetuating them unnecessarily, and thus tempting the reckless to folly, or the ordinarily cautious to needless error.

FURTHER FACTS AS TO PILE DRIVING FORMULAS.

(From Engineering News of Oct. 19, 1889.)

We review at some length in another column Prof. Ira O. Baker's new "Treatise on Masonry Construction." Of the book in general we have been gratified to be able to speak in the highest terms. Of what is given on the subject of pile-driving we were unable to speak so highly, and as the subject is a broad one, and one which it is quite desirable should be reduced to some basis of general agreement, and as Professor Baker gives some new data on the subject, it seemed much better that we should make the subject one for general discussion.

In our issue of Dec. 29, 1888, we discussed this same question at some length, using as a text a letter from Mr. John C. Trautwine, Jr., and an admirable paper by Mr. Rudolph Hering, giving a comparative abstract of some fifteen different formulas. The conclusion we reached was "that there is no better or safer formula than the following for the safe working load for piles under all ordinary conditions, to be reduced under exceptional conditions (as notably with irregular penetration), but never exceeded unless under special circumstances, viz.:

$$L = \frac{2\,w\,h}{s+1},$$

in which L = safe working load in pounds, tons or other units; w = weight of hammer in the same unit; h = fall of hammer in feet, and s = last penetration in inches, assumed to be sensible and at an approximately uniform rate (and head of pile in good condition, as elsewhere expressed). The formula is at least consistent and cannot lead astray, as many others are likely to do.

To the miscellaneous assortment of formulas here alluded to, Professor Baker has now added another and we propose to show: (1) why we distrust his formula also for practical use, and (2) why his additional data confirm our belief that the above simple formula is really the best and safest, as well as the simplest, of any now before the profession. That the reader may have before him the grounds on which we originally based this conclusion, we reprint in another column some liberal extracts from our former article.

Professor Baker's "formula for practice" is in reality the following interesting equation, to duly express which we shall have to give it in two installments:

$$P = \sqrt{W\,h\,\frac{12\,S\,E\,s\,e}{3\,L\,s\,e + 4\,l\,S\,E} + \frac{36\,d^2\,S^2\,E^2\,s^2\,e^2}{(3\,L\,s\,e + 4\,l\,S\,E)^2}} - \frac{6\,d\,S\,E\,s\,e}{3\,L\,s\,e + 4\,l\,S\,E}.$$

The author eliminates a handful or so of these variables, it is true, including length (L) and section (S) of hammer, length (l) and section (s) of pile, and elastic modulus of hammer (E) and pile (e) by letting

$$q = \frac{6\,S\,E\,s\,e}{3\,L\,s\,e + 4\,l\,S\,E},$$

when the above long equation reduces to

$$P = \sqrt{2\,q\,W\,h + q^2\,d^2} - q\,d.$$

By assigning certain assumed average values to the several variables in q, he further obtains a numerical constant of 5,000 for q, giving the equation the form:

$$P = 100\,(\sqrt{W\,h + 50\,d)^2} - 50\,d),$$

in which P = the ultimate load in tons which will move the pile, W = weight of hammer in tons, h = fall of hammer in feet, and d = last penetration in feet.

This form, the author tells us in italics, "is the form to be used in practice" (p. 239); yet immediately thereafter (p. 245) he tells us that "if it is thought not desirable to trust entirely to theory, then the above equations may be considered as giving only the form, and q be determined by experiment." Four pages later he tells us that "the factor of safety ranges from 2 to 12, according to the importance of the structure and to the faith in the formula employed," which leaves a range of 600% for the inner consciousness to work in, and makes any great elaboration in the formula ridiculous, while on the very next page we have the amazing declaration: "In a few cases a small settlement has taken place in a railroad trestle when the factor of safety was 3 or 4, as computed by equation (4), page 239."

We must confess our inability to comprehend that state of mind among scientific writers which so frequently enables them, as in this case, to say on one page that a proper safety factor for a given formula ranges "from 2 to 12," and on the very next page that failure has been known to occur under a factor of 3 to 4. Where does the element of scientific precision or caution come in, if it be admissible to put forward a formula as giving a proper assumption for ultimate load which in a few cases (out of the very few which it is possible to examine) prove three or four times too large? It may be claimed, however, as is done in behalf of separate wheel loads for computing bridge strains, that such a formula, while it has no absolute precision, is at least correct in form, and hence leads to an evener distribution of strength and material under varying conditions. We propose to show, therefore, that, even from this point of view, the more elaborate formula is also the less correct.

For this purpose we may also use as a primary basis for comparison a paper which is one of the many new references in Prof. Baker's valuable work, and which has heretofore escaped our attention, viz., a paper by Mr. A. C. Hertiz, giving actual records of the driving and subsequent pulling up of nearly 400 piles,* and hence have a more solid experimental basis than most other papers on piles. Mr. Heritz found the following relation:

$$d = \frac{Wh}{P} - \frac{P}{500}$$

which Prof. Baker transforms into the equation

$$P = \sqrt{500\ W\ n + (250\ d)^2} - 250\ d.$$

justly remarking that it has precisely the form of his own equation for practice, though deduced in an entirely different way. Let us see precisely how much this identity of form means, however. by working out a few numerical examples to cover the range of ordinary practice.

The extreme range in last penetrations may be said to be from 0½ to 5ins., or say 0.05 to 0.4 ft. The extreme fall ever used may be said to be 30 ft. for last blows, and the extreme weight of hammer 1½ tons or thereabouts. Regarding W h as a compound unit, as we can do by any of the formulas, values of 10, 20, 30 and 40 ft.-tons will cover all necessary range, and tabulating on this basis we get the following rather striking comparison between the Baker formula, Hertiz formula and our own simple rule of

$$\text{Safe load} = \frac{2wh}{s+1}.$$

Ultimate Resistance (Value of P) by Baker's Formula.

Wh = ft.-tons of blow.	Last penetration in feet, d = 0.05	0.1	0.2	0.3	0.4
	Ultimate Resistance of Pile.				
10	153.1	91.6	48.8	33.0	24.8
20	262.3	170.8	95.4	65.3	49.5
30	352.1	241.6	140.2	96.9	73 6
40	430 1	306.2	183.2	127.9	97.6
Ultimate Resistance as Deduced by Hertiz from Records of 400 Piles.					
10	59.3	50.0	36.6	28.1	22.5
20	88.3	78.1	61.8	50.0	41.4
30	110 6	100.0	82.3	68.6	58.1
40	129.5	118.6	100.0	85.1	73.2

* Proc. Inst. C. E., lxiv., 311-315; republished in Van Nostrand's Magazine, xxv., 373-6.

Safe load by Engineering News Formula $L = \frac{2wh}{s+1}$

10	12.5	9.09	5.88	4.35	3.45
20	25.	18.18	11.76	8 70	6.90
30	37.5	27.27	17.65	13.04	10.34
40	50.	36.36	23.53	17.39	13.79

It needs but the most cursory comparison of these tables to see at once that in the two great tests of reasonable absolute values and of the relation of the different values to each other, the two formulas for ultimate load, which have "exactly the same form," are much less symmetrical with each other than is the simple safe-load formula which we have proposed with either of them. In the first place, the Baker formula gives much greater safe loads than the Hertiz, as shown in detail as follows:

Ratio of Excess of Ultimate Loads by the Baker Formula Over Those by the Hertiz.

	Last penetration in feet.				
Wh	.05	.1	.2	.3	.4
10	2 57	1.83	1.33	1.17	1.11
20	2.97	2.18	1.54	1.31	1.20
30	3.17	2.42	1.70	1.51	1.27
40	3.33	2.58	1.83	1.50	1.33

	Ratios.	
Taking the four corners of this table illustrating extremes, they stand..............	2.57	1.11
	3.33	1.33
Comparing in like manner the four corners of the last two tables, showing the excess of the Hertiz ultimates over our own safe loads, they will stand.......................	4.75	6.50
	2.50	5.30
Comparing our own safe loads with the Baker ultimates, similarly they will stand	12.2	7.2
	8.6	7.1

It will at once be seen by the careful reader that the simplest formula "splits the difference" between these two more elaborate forms, so as to come closer to either of them in its ratios than they do to each other. We agree with Mr. Baker in his evident feeling that the Hertz formula is not entitled to full credence as to absolute values. Nevertheless, it is notable that under all conditions his own, of "exactly the same form," gives from 10 to

233% larger ultimate loads, never giving less. We shall show shortly that this results from an actual defect of form, and it tends somewhat to explain why certain piles have failed under one-third to one-fourth of his ultimates. It should be added in fairness, however, that these ultimates correspond very well with those of the hatful of other formulas reviewed in our issue of Dec. 29, 1888, showing about a mean between them at what we may call the unit value, that for 30 ft. fall of 2,000lb. hammer with 0.1 penetration.

Now, in the first place, is it in fact warranted by good practice to load piles with larger loads than are given by the Engineering News formula as tabulated above? We do not think so. Calling the weight of masonry 2 tons per cu. yd., the above table permits of loading piles, 3 ft. between centers, with 50 to 75 vertical ft. of solid masonry, and piles 2½ ft. between centers with 75 to 110 ft. of masonry. More, we believe, is never warranted, and never imposed by careful engineers. The proper alternative is to step out the foundation to give more area until enough is secured. Prof. Baker, on page 248, quotes examples (which we might well extend) showing 13½ to 20 tons per pile, but although the piles under the exceptional Royal Border bridge carry 70 tons, yet as Mr. Trautwine would say, "it is a wretched precedent for bridge building." On the other hand, he quotes an example of some piles driven in a work under the supervision of one of the editors of this journal,* which leads to a quite opposite conclusion, as follows:

The South St. bridge approach, Philadelphia, fell by sinking the foundation piles under a load of 24 tons each. They were driven to an absolute stoppage by a 1-ton hammer falling 32 ft. They were driven through mud, then tough clay, and into hard gravel. . . . It is more probable that the

*See Trans. Am. Soc. C. E., vol. vii. (1878), p. 264.

lost blow was struck on a broomed head, which would greatly reduce the penetration, and that consequently their supporting power was overestimated. According to Trautwine's formula—the only one of all the preceding which is even approximately applicable to this case —their supporting power was 164 tons.

The author is in error in supposing the piles were broomed. That was carefully avoided. As an instructive instance, which now is almost forgotten, of the dangers besetting the piledriver, we reproduce in another column from Trans. Am. Soc. C. E. a cut showing the conditions, with an explanation of the facts. No formula could be properly applicable to this case, but the author errs in saying that Trautwine's formula is the only one he gives which is "even approximately applicable." His own is perfectly applicable, with the sole exception that it gives an absurd result. Since $d = 0$ it reduces to

$$P = 100 \sqrt{wh}$$

whence we find the sustaining power of these piles ought to have been 565.7 tons! A formula which becomes absurd under extreme conditions is ipso facto shown to be defective in form. Nor is it necessary to make the conditions very extreme to know this. Had d been ¼ or ½ or ¾ in. we should have obtained the almost equally absurd results of 474.5, 400.0 and 340.3 tons respectively. Under the same conditions the Engineering News formula would give

	For s = 0	S = ¼-in.	S = ½-in.	S = ¾-in.
Safe load =	64 C tons.	56.2 tons.	42.7 tons.	36.5 tons.

These are just about such loads as ordinary practice would warrant, and this brings us to what is our principal objection to the more elaborate formulas given, which is that they are even theoretically defective, in giving far too great proportional loads for the smaller penetrations, for a reason well expressed by the author himself: "No formula can be accurate which does not, in some way, take cognizance of the condition of the head of the pile." The s + 1 factor does this; the more elaborate formulas do not do it; the Trautwine $\sqrt[3]{h}$ formula does far too much of it.

We therefore feel that we are even better justified than before in recommending to the profession the simple formula

$$\text{Safe load} = \frac{2\,w\,h}{s+1}$$

(in which w = weight of hammer in same unit as safe load, h = fall in feet and s = last penetration in inches) as not only the simplest but the safest and best for practice. In so very uncertain a matter it is wrong in principle to start from high ultimates which are certainly unsafe as a unit, and allow foolish men to deceive themselves with the notion that they are being cautious when they divide it by three or four, when they are really running great risks. The carnal mind longs for this comforting assurance, but the true formula for pile-driving is one which is certainly safe in any kind of uniform material, leaving the engineer to realize that he is running risks (which yet may be justified and reduced by caution), if in special cases he goes beyond it.

THE COST OF PILE DRIVING.

(From Engineering News of Dec. 14, 1889.)

From Prof. Ira O. Baker's treatise on Masonry Construction, we extract, by permission of the author, the following data as to the cost of driving piles under different conditions. It will be noted that the figures are taken from actual practice of recent date; and therefore may be taken as reliable guides in making up estimates.

Cost of Piles.—At Chicago and other points on the Mississippi above St. Louis, pine piles cost from 10 to 15 cts. per lin. ft. according to length and location. Soft-wood piles, including rock elm, can be had in almost any locality for 8 to 10 cts. per ft. Oak piles 20 to 30 ft. long cost from 10 to 12 cts. per ft.; 30 to 40 ft. long, from 12 to 14 cts. per ft.; 40 to 60 ft. long, from 20 to 30 cts. per ft.

Cost of Pile Driving.—There are many items that affect the cost of work which cannot be included in a brief summary, but which must not be forgotten in using such data in making estimates.

Below is the cost for a number of classes of work:

Railroad Construction.—The following table is a summary of the cost, to the contractor, of labor in driving piles (exclusive of hauling) in the construction of the Chicago branch of the Atchison, Topeka & Santa Fe R. R. The piles were driven, ahead of the track, with a horse-power drop-hammer weighing 2,200 lbs. The average depth driven was 13 ft. The table includes the cost of driving piles for abutments for Howe truss bridges, and for the false work for the erection of the same. These two items add considerably to the average cost. The contractor received the same price for all classes of work. The work was as varied as such jobs usually are, piles being driven in all kinds of soil. Owing to the large amount of railroad work in progress in 1887, the cost of material and labor was about 10% higher than an average of the year before and after. Cost of labor on piledriver: one foreman at $4 per day, six laborers at $2, two teams at $3.50; total cost of labor = $23 per day.

Cost of Pile Driving in Railroad Construction.

Number of piles included in this report	4,409
Number of lineal feet included in this report	109,578
Average length of piles	24.8
Number of days employed in driving	494
Number of lineal feet driven per day	221.8
Cost of driving per pile	$2.53
Cost of driving per foot	10.4 cts

Railroad Repairs.—The following are the data of pile driving for repairs to bridges on the Indianapolis, Decatur & Springfield R. R. The work was done from Dec. 21, 1885, to Jan. 5, 1886. The piles varied from 12 to 32 ft. in length, the average being a little over 21 ft. The average distance driven was about 10 ft. The hammer weighed 1,650 lbs.; the last fall was 37 ft., and the corresponding penetration did not exceed 2 ins. The hammer was raised by a rope attached to the drawbar of a locomotive—comparatively a very expensive way.

TABLE 26.

Cost of Piles for Bridge Repairs.

Items of Expense.	Total.	Per Pile.	Per ft. Cts.
Labor: Loading and unloading piles, 7⅛ days	$16.00	$0.08	0.4
Bridge gang, driving, 12 days	153.75	0.78	3.7
Engine crew, transportation and driving, 13 days	45.90	0.23	1.1
Train crew, transportation and driving, 13 dys.	71.50	0.37	1.6
Supplies: Engine supplies	23.49	0.13	0.5
Six pile rings and two plates	13.29	0.06	0.3
Repairs	11.04	0.05	0.3
Total expense for driving	$334.95	$1.70	7.9
Material: 4,192 ft. oak piles at 13 cts	$565.92	$2.68	13.5
Total cost	$900.89	$4.56	21.4

On the same road, 9 piles, each 20 ft. long, were driven 9 ft. for bumping posts, with a 1,650-lb. hammer dropping 17 ft. The hammer was raised with an ordinary crab-winch and single line, with double crank worked by four men. The cost for labor was 8.3 cts. per ft. of pile, and the total expense was 21.8 cts. per ft.

Bridge Construction.—The following table gives the cost of labor in driving the piles for the Northern Pacific R. R. bridge over the Red River, at Grand Forks, Dak., constructed in 1887. The soil was sand and clay. The penetration under a 2,250-lb. hammer falling 30 ft. was from 2 to 4 ins. The foreman received $5 per day, the stationary engineer $3.50, and laborers $2.

TABLE 27.

Cost of Labor in Driving Piles in Bridge Construction.

Kind of Labor.	Pile bridge on land.	Temporary bridge.	Draw fender and ice breaker.	Pivot pier.	River pier.
Preparation and repair of plant........	$68.95	$63.65	$53.50	$37.00	$61 60
Driving...........	432.70	25[illegible].92	430.50	515.45	565.80
Sawing and straightening	78.75	....	47.50	179.80*	131.90†
Total cost.........	$580.40	$316.57	$531.50	$432.25	$459.30
No. of piles in the structure	224	102	104	121	167
Total No. of ft. remaining in the structure...........	7,238	3,710	7,023	4,639	7,316
Average length of piles remaining in the structure......	32.3	......	38.2	38.4	43.8
Average length of piles cut off.........	1.1	......	4.1	6.6	3.7
Cost per ft. of pile remaining in the structure	8.0 cts.	8.5 cts.	7.6 cts.	9.3 cts.	10.4cts.

Average cost for driving, per ft., remaining in the structure = 8.8 cts.

* Sawed off under 8 ft. of water.

† Including $70.25 for excavating and bailing in order to get at tne sawing.

Foundation Piles.—The contract price for the foundation piles—white oak—for the railroad bridge over the Missouri River, at Sibley, Mo., was 22 cts. per ft. for the piles and 28 cts. per ft. for driving and sawing off below water. They were 50 ft. long, and were driven in sand and gravel. in a coffer-dam 16 ft. deep, by a drop-hammer weighing 3,203 lbs., falling 36 ft. The hammer was raised by steam power.

In the construction of a railroad in southern Wisconsin during 1885-87, the contract price—the lowest competitive bid—for the piles in place under the piers of several large bridges averaged as in the following table. The piles were driven in a strong current and sawed off under water, hence the comparatively great expense.

TABLE 28.

Contract Price of Foundation Piles.

Material of Pile.	Kind of driving.	Contract price per lineal ft.: For part remaining in structure.	Contract price per lineal ft.: For pile heads sawed off.
Rock Elm....	Ordinary....	40 cts.	15 cts.
Pine..........	"	40 "	20 "
Oak	"	48 "	25 "
Oak	Hard...	50 "	30 "

In 1887 the contract price for piles in the foundations of bridge piers in the river at Chicago was 35 cts. per ft. of pile left in the foundation. This price covered cost of timber (10 to 15 cts.) driving, and cutting off 12 to 14 ft. below the surface of the water, about 17 ft. being left in the foundation.

The cost of driving and sawing off may be estimated about as follows: (17 + 13) ft. of pile at 13 cts per ft. = $3.90; 17 ft. of pile, left in the structure, at 35 cts. per ft. = $5.95, $5.95 − $3.90 = $2.05 = the cost per pile of driving and sawing off, which is equivalent to nearly 7 cts. per ft. of total length of pile. In this case the waste or loss in the pile heads cut off adds considerably to the cost of the piles remaining in the structure. In making estimates this allowance should never be overlooked.

Harbor and River Work.—In the shore-protection work at Chicago, done in 1882 by the Illinois Central R. R., a crew of 9 men, at a daily expense, for labor, of $17.24, averaged 65 piles per 10 hours in water 7 ft. deep, the piles being 24 ft. long and being driven 14 ft. into the sand. The cost for labor of handling, sharpening, and driving was a little over 26 cts. per pile, or 1.9 cts. per ft. of distance driven, or 1.1 cts. per ft. of pile Both steam-hammers and water-jets were used, but not together. Notice that this is very cheap, owing (1) to the use of the jet, (2) to little loss of time in moving the driver and getting the pile exactly in the predetermined place, (3) to the piles not being sawed off, and (4) to the skill gained by the workmen in a long job.

On the Mississippi River, under the direction of the United States Army engineers, the cost in 1882 for labor for handling, sharpening, and driving, was $3.11 per pile, or 20 cts. per ft. driven. The piles were 35 ft. long, the depth of water 15.5 ft. and the depth driven 13.6 ft. The water jet and drop-hammer were used together. The large cost was due, in part at least, to the current, which was from 3 to 6 miles per hour.

MR. FOSTER CROWELL ON PILE DRIVING FORMULAS.

(From Engineering News of Oct. 27, 1892.)

In our issue of Dec. 29, 1888, we published an article under the head of "Formulas for Safe Loads of Bearing Piles," in which we analyzed at some length the various existing formulas for pile driving and proposed the following formula for general use, as simpler and more trustworthy than any of them:

$$L = \frac{2\ wh}{s + 1}$$

in which L = the SAFE load on the pile in any unit of weight, w = the weight of hammer on the same unit, h = the fall of hammer in feet, and s = the set of pile under the last blow in inches, determined in practice by computing the mean set under several of the last blows.

This formula has since become somewhat widely known and used as the "Engineering News" formula, and it has lately been made the subject of a new investigation by Mr. Foster Crowell, in a paper before the American Society of Civil Engineers* of which an abstract follows, in which he indorses the formula as on the whole the most convenient and reliable of all, but proposes a modification of it under which the constant 1 of the denominator is divided into three different terms, only one of them a constant. An exceptionally full and valuable discussion followed, which we also abstract.

After a short preamble stating the need for more general adherence to some recognized standards for pile driving, Mr. Crowell continues:

At the outset it may be well to bear in mind that in order to discuss the subject intelligently, we must keep separate the extreme sustaining power of any pile under a static load, and the character of the particular use or stress to which the pile is to be subjected. We will first consider a series of differing values, obtained by several different recognized formulas, for the sustaining power of the same pile under exactly the same conditions; we will then examine those formulas in detail and endeavor to select the most satisfactory one as a general formula for practical use; and, finally, we will study the consistent application of the formula so selected, to the varying conditions met with in actual practice.

Rudolph Hering, M. Am. Soc. C. E., in a very valuable monograph on Bearing Piles,* which cannot be too highly recommended as a most useful work of reference, has collated and tabulated no fewer than 14 different formulas attributed to 10 different authorities, which give 14 different values for the extreme sustaining power of the same pile, driven under precisely similar conditions; the values range in a typical case, all the way from 96,000 to 600,000 lbs., without taking into consideration the further differentiation resulting from varying views as to suitable coefficients of safety, which run anywhere from ½ to 1-100, so that if we were considering the working load for a given pile under extreme conditions, we should find it by one authority to be 4,500 lbs.; by another, 16,000; by a third, 48,000; by a fourth, 75,000; by a fifth, 120,000, and so on. It is to be remarked that one of the most eminent of the authorities gives five different formulas of varying theoretical exactitude, two others each give two forms to be used in separate cases, which in practice is quite difficult, even for an expert, to choose between; while none of the authorities attempt, except in the most general way, to make any classification of applications, but leave that entirely to the individual judgment, within very wide margins. This is most perplexing to those whose need of a working formula is most urgent and, in connection with the difficulty of making a correct prognosis, naturally tends to produce the great disparities in practice which we have noted, and which it should be our aim to avoid in order to attain to absolute economic security. The list of formulas

* Reprinted later in this volume.

best known, and which represents practically all the valuable literature on the subject, is as follows:

Weisbach..................................in five forms.
Sanders.........................one form of Weisbach.
Mason..........................one form of Weisbach.
Trautwine.................................in two forms.
Rankine.
Rondolet.
Redtenbacher.
Brix and Becker.........................in two forms.
Nystrom.
McAlpine.
Engineering News.

Fig. 1 exhibits the deduced values of extreme sustaining power, and the ordinary and the minimum loads, recommended by each authority in the case of a typical pile driven under ordinary conditions. The purpose of this diagram is merely to show variations in results.

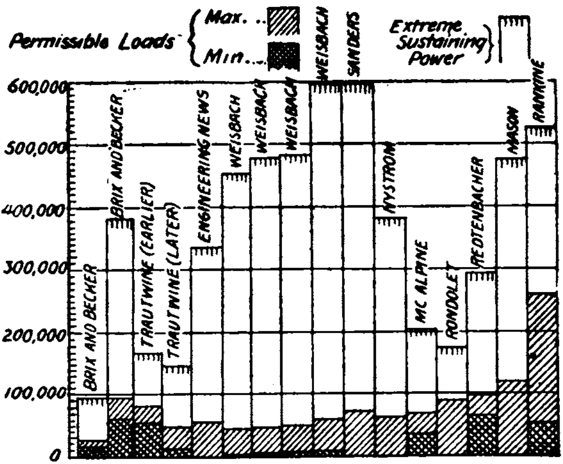

Fig. 1, Showing Differing Values by Various Formulas, in the Case of a 2000-Lb. Ram Falling 30 Ft. with Set of .1 Ft. (= 1.2 Ins), of Extreme Sustaining Power and Permissible Loads.

It is evident from inspection of Fig. 1, that the authorities, as has already been stated, differ, not only as to safe loads, wherein there is reasonably room for such divergence, but also to a very marked extent in the theoretical extreme sustaining power. The "factor of safety," too, seems to be entitled to the nickname once bestowed upon its cousin of the iron bridge. But if we look a little closer at the forms of the formulas we shall see why such variations occur, and may perceive that if we had taken some other case, with a different weight of hammer and different fall, we should have obtained another, but quite different, set of variations, and so for every assumed case.

For our present purpose it will not be necessary to review the entire list of formulas, a few being sufficient for illustration. All the formulas are based, of course, upon the mechanical principle of accumulation of work.

If regarded as a mere question of dynamics, and if we could eliminate the elasticity and comprehensibility of hammer, pile and soil; neglect the consideration of their relative weights, and the frictional and other resistances to the motion of the hammer; then the theoretical resistance, or sustaining power of the pile would be found in the simple expression:

$$\text{Sustaining power} = \frac{\text{Weight of ram} \times \text{fall}}{\text{Space through which the hammer moves after reaching the pile.}}$$

But we cannot, as a matter of course, treat the matter thus simply, for it is in reality a very complex case of impact, wherein the exact application of principles to any particular case is well-nigh impossible under ordinary working conditions where the falling ram is used; but which the various authorities have sought to meet either with varying degrees of theoretical minutiae, or by means of working factors sufficiently comprehensive to cover all cases. Some of the formulas take into consideration the compressibility and weight of pile; others neglect one or both. It is easy, therefore, to see that they must differ. None regard the compressibility of the soil as a necessary element in the calculation, nor introduce specific factors of mechanical friction and air resistances as applied to the falling ram. The proper weight ratio of pile and hammer to secure the best results has received theoretical consideration, but as it would be extremely inconvenient and, in fact, impracticable, to select piles of definite weight, it is rightly regarded as a matter to be considered generally. The ram should always be at least as heavy as the pile; generally, in practice, it is from 25 to 200% heavier than piles which may be used in the same work.

It is evident, further, that, however interesting and involved the theoretical study of this question may be, a working formula should contain only those essential factors which can be readily obtained with reasonable correctness in the case of any pile, and it is not worth while nor sensible to waste time in refining a result beyond the refinement of the data. The frictional and air resistances can, however, be experimentally rated by chronographic methods once for all in the case of any particular machine, if that refinement be desirable, and expressed as a decrement for the actual fall. The Trautwine formula, which is probably used more extensively than any other in this country, takes no account of compressibility, weight of pile, or directly of frictional resistance to fall of ram, but considers the work done by the ram to vary as the cube root of the fall. While there is justification for this assumption in dealing with average falls, based upon increased air resistance and greater impact losses, yet the allowance would appear to be too great, giving too low values for the higher falls, and excessive results for very low ones.

In most situations it is necessary to treat piles individually in order that all in any group may be given the same measure of stability under varying conditions observed in driving, so that it is essential to apply the formula to every pile. On this account the form of a working formula is a matter of great importance, and to insure rapid and correct results it must be a simple expression involving only such data as can be quickly and correctly obtained for each pile, and requiring the minimum of computation for instantaneous application.

The only data that can be readily obtained are the weight (w) and the fall (h) of ram, and the penetration (s). The weight of the pile and its compressibility cannot be conveniently determined, and are so modified often by considerations of specific gravity and resilience that they would be of no practical account. In addition to that any "brooming" of the pile-head acts as a cushion, to an extent which completely discounts the theoretical natural compressibility. The consideration of brooming, like other mechanical questions which present themselves in connection with the art of pile-driving, does not properly come within the scope of this paper. A very instructive and precise record of the enormous cushioning effects due to this cause, as observed in a number of piles driven by a Nasmyth steam hammer, is contained in a very valuable paper on steam pile-driving, by D. J. Whittemore, Past President Am. Soc. C. E.*

If the proposition be accepted that we may profitably discard all working formulas, excepting those that involve only correct and accessible data, we may select from the foregoing list for further comparison the three following typical forms, rejecting the others as being either unnecessarily refined and unsuitable, or inconveniently cumbrous. In all three the notation is as follows:

w = weight of ram in pounds. h = height of fall in feet. s = penetration under last blow, in inches. F = working factor. L = load in pounds.

1. Weisbach (i. e. the form of Weisbach, wherein compressibility and weight of pile and elasticity of ram are neglected; this is usually known in America as Sanders').

$$L = F\frac{wh \times 12}{s},\ F = \tfrac{1}{8} \text{ to } \tfrac{1}{8}.$$

2. Trautwine (i. e. the form of Trautwine, wherein the pile is assumed to "sink appreciably, say, a few inches," under the last blow. In the later editions of this authority, the other form, for smaller penetrations, has been dropped and this is made general. See "Trautwine's Engineer's Pocket Book," 1889).

$$L = F\frac{\sqrt[3]{h} \times 50\ w}{s + 1},\ F = \tfrac{1}{2} \text{ to } \tfrac{1}{12}.$$

3. Engineering News. (This name has been given to

* Given elsewhere in this volume.

this form to distinguish it, the name of its originator not being known to the author; it first appeared in Engineering News of Dec. 29, 1889)

$$\text{Safe load} = \frac{2\ wh}{s + 1}.$$

It will be noted that Nos. 1 and 3 are alike in the respect that each gives similar results for equal ram-energies, expressed in foot-pounds, irrespective of the fall, whereas No. 2 introduces a theoretically illogical variation in this product, which, together with the practical inconvenience of using the cube root in rapid application, without any gain in accuracy, would give preference, as far as form alone goes, to either No. 1 or No. 3 as a working formula.

In order to compare readily the results obtained under a variety of conditions, Fig. 2 has been prepared, exhibiting the respective values of safe static loads as given by the three formulas, in four cases of varying height of fall, with penetrations ranging from ¼ in. to 3 ins. under constant weight of ram. Were it not for the presence of the cube root in the Trautwine formula, one case instead of four would have been sufficient for comparing the three formulas. It is interesting to trace the effect of this factor through the successive plottings and to note that it is by no means inconsiderable, even within the comparatively limited range of fall.

The distinctive curves are plotted to abscissas of penetration in inches (value of s) and ordinates of working loads (values of L). As the Trautwine formula in its earlier form contained a somewhat higher coefficient and a maximum factor of ½ instead of ⅙, two Trautwine curves are necessary to make the comparison comprehensive, the more modern form giving the lower values. In order to show graphically the effect of the constant "c" in the Engineering News formula and to prepare for reference further on to a suggested modification of this formula, the curve, shown by the full line of the equation

$$L = \frac{w \times 2\ h}{s + (c = 0.3)}$$

has been introduced. In the Weisbach-Sanders formula

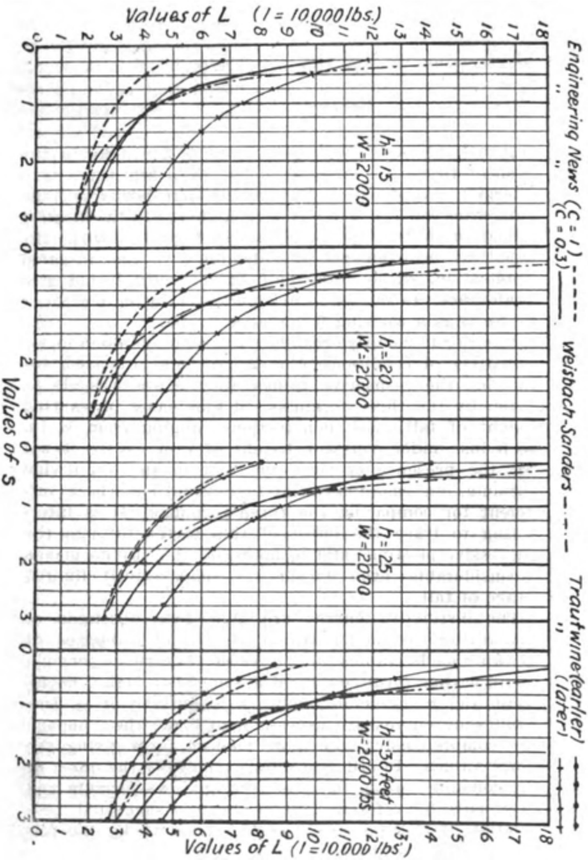

FIG. 2. SHOWING DIFFERING VALUES BY VARIOUS FORMULAS IN FOUR CASES WITH VARYING FALL AND VARYING PENETRATION UNDER CONSTANT WEIGHT OF RAM.

F is taken at ⅛, and in all four cases w is taken at 2,000 lbs., h being 15, 20, 25 and 30 ft., respectively. Values of L are given in pounds, to the nearest thousand.

It is hardly necessary to mention that these curves are merely graphic representations having no generic value. But their comparison is instructive and we are struck by two practical considerations: first, that where the values of s are from ½ in. to 1 in., there is a closer approach to uniformity in the formulas than when s is either greater or less; second, the Engineering News' functions with constant (c = 1) gives values more and more conservative, comparatively, as the values of s become smaller, whereas the curve with c taken at 0.3, while growing conservative as s becomes greater, maintains more nearly an average of the other two where s is smaller. The first observation implies that the experiments preceding the adoption of all three formulas were conducted within a comparatively narrow range of falls; while the second points to the use of the lower value of c as being more logical, for it will be admitted that, other things being the same, the smaller the penetration, the greater the expectation of stability of the support to the pile, as well as the initial sustaining power of the pile itself. Proceeding a step further we find that the c curves converge in the direction of greater penetration, but preserve their conservative quality; whereas, in the opposite direction the Sanders curve gradually passes entirely out of the field of practicability. The conclusion seems to be warranted, therefore, that with a suitable value for c, the Engineering News' formula is more reliable and rather more convenient in practical use than Trautwine's, and equally as convenient and more conservative than the Weisbach-Sanders. It is to be borne in mind that within the range of moderate penetration (2 ins. or less) ample experience has demonstrated that for ordinary conditions any one of the three gives safe results.

In the discussion of the third division of our subject, the consistent application of the formula to varying conditions, the value of c will be considered.

We have seen that the form of formula No. 3, $L = \frac{2\,wh}{s + c}$ is the simplest, and that its results are reliable and conservative. If, then, it is found to be applicable to all cases without change of form, and, in addition, to be readily adaptable to classification, it will be suitable as a basis of uniform practice and also as a means hereafter of increasing our practical knowledge of the efficiency of bearing piles, by accumulating comparable results. The writer offers, as the only feature in this paper for which originality is claimed, a development of the formula which lends itself in a very elastic and consistent manner to the desirable end. It consists simply in making c a tangible variable for natural conditions, and a selective variable within limits according to the requirements of the case. In order to make this perfectly clear we should consider that there are three general cases in which modification may be necessary:

1. Where the load is static and known, but the natural support for the piles is insecure or doubtful.
2. Where the support is reliable, but the load is dynamic.
3. Where the support is not reliable and the load is dynamic.

In the first case, the variation can generally, though not always, be gaged by the resistance of the material into which the pile is driven, under what may be termed a standard blow. The writer considers that a 2,000-lb. ram falling 20 ft., or an equivalent product of 40,000 ft. lbs. on a 12-in. pile, constitutes a convenient standard for this purpose, and when the standard blow, or a series of such blows, is delivered on any pile, the observed penetration should in a majority of cases afford a tangible measure of the security of the stratum. If, then, we substitute for the constant value of c a series of values based on the above considerations, we can readily determine with practical correctness how to deal with pile-beds of various degrees of firmness.

The rule adopted by the author is to make c (for static loads) $= .1 + n$ wherein .1 is an arbitrary constant, introduced to prevent exaggerated values of L with very small values of s, and n is made equal in the case of each pile to half the square root of the maximum penetration of the pile under a blow of 40,000 ft.-lbs. or more.

Table 1 gives corresponding values of n for different penetrations, and shows that within the extremes of penetration of about 1-6 in. to 3 ins. under the standard blow the values of c vary from .3 to 1, these being the values for the two curves of this formula in Fig. 2, which we have considered.

In the second case the selective variable should be

TABLE 1.

A General Pile-Driving Formula.

For Static Loads:

$$L = \text{the working load} = \frac{2\,wh}{s + .1 + n};$$

w is weight of ram; h is virtual fall in feet; s is set in inches under last blow.

For Dynamic or Vibratory Loads:

$$L = \frac{2\,wh}{s + .1 + n + n'}.$$

n is a function of the observed penetration, s′, in inches, under a standard blow of 40,000 foot pounds n′ is an arbitrary variable which is dependent upon the character of the pile duty.

Values of n.	$n = \frac{\sqrt{s'}}{2}$	Values of n′ according to duty. classification.	
s′.		n′.	Classification.
⅛ inches.	.175	.1	Large buildings to contain light machinery in motion.
¼ "	.250	.2	Long span bridge abutments for railways.
½ "	.354	.3	Long span bridge abutments for highways.
¾ "	.433	.4	Buildings to contain heavy machinery in motion.
1 "	.500	.45	Short span bridge abutments for trestles for railways.
1¼ "	.559	.5	Short span bridge abutments for highways.
1½ "	.613	.55	Buildings subject to extraneous vibration.
1¾ "	.662	.6	Foundations for machinery.
2 "	.707	.7	Elevator towers in ordinary cases.
2¼ "	.750	.75	Bridge piers exposed to current vibration.
2½ "	.791	.8	Light houses exposed to ordinary wave action.
2¾ "	.830	.9	Foundations for turn-tables.
3 "	.866	.95	" " pivot bridges.
3¼ "	.900	1.	Chimney stacks exposed to winds.
3½ "	.936		
3¾ "	.965		
4 "	1.		

used, and here the engineer must be guided by his experience or the experience of others as to the value of n' to be selected; this will be further considered.

In the third case both the tangible and selective variables of n and n' must be introduced.

The extreme case in which this formula should be used under the most favorable circumstances, is for a penetration of ⅛ in., as it is difficult to measure smaller penetrations with sufficient accuracy. The maximum value of L, therefore, (using $c = .275$, as given in the table), for $s = 0 +$ would be

$$L = \frac{2\ wh}{.275} = 7.3\ wh,$$

which as h is expressed in feet and s in inches, gives a working factor still of $12 \div 73 = 1.7$. But we should attach little value to small sets, which must always be viewed with suspicion, and often, moreover, indicate results beyond the crushing strength of the pile.

This table applies solely to bearing piles; the results are to be taken only when found not to exceed safety as against fibre-crushing, or as against buckling in cases wherein the pile acts, wholly or in part, as a column.

In this consideration the author has purposely confined himself to piles proper and has not extended it to pillars or columns, which they sometimes become when driven through a soft stratum to an unyielding bottom, or into a denser lower stratum. In all such cases great care and discrimination is necessary as to what extent results given by the pile formulas can be used, and also as to the limitation of driving. These formulas are only for determining the efficiency of piles to distribute, throughout the stratum, loads which its surface cannot sustain. It is quite possible to overload the stratum by driving piles too thickly; it is sometimes thought that if three piles, for instance, are good in a certain area, six will "make assurance doubly sure;" this policy is not only costly and foolish, but in many cases it is dangerous. A certain public building in New Orleans, of which the author has heard, stands on an enormous number of square piles driven so as to touch one another; in other words, there is a solid wall of wood, and instead of each pile having four surfaces in contact with the sustaining stratum, only the outer rows have contact, and they but on two surfaces; there are, therefore, from four to six times too many piles used and the support is still much less than could have been obtained.

There seems to be objection in many quarters to piles for foundations of buildings, which is not warranted in the light of their record in engineering structures, and which greater care and closer economy in their use should dispel. As a rule, in the author's judgment, their sustaining powers are greatly underrated, and too much importance is attached to small "sets." He has before him the specifications for a large structure to rest on piles, which require that "all piles shall be driven to a half-inch set from a 2,500-lb. hammer falling 25 ft.," and the plans are drawn with the idea that that degree of firmness in each pile can and will be secured. Possibly experimental driving has already determined that the expected conditions will be found, but it is more than likely that in driving the piles, either considerable latitude will be taken or an excess of length will be used. Sometimes in the search for firm bottom, successive tiers of piles have been driven, one presumably on top of the other, to great depths; whereas, if an equal number of piles, or, better still, if a smaller number, but of larger diameter, had been driven in one tier, much greater actual stability would have been secured with greater economy.

The author then closes his paper with a short discussion of the effect of the "selective values of n'" which is more clearly shown, we think, by the table which follows in Mr. Wellington's discussion.

The discussion of Mr. Crowell's paper was opened by Mr. A. M. Wellington, as follows:

As the author of the formula which Mr. Crowell has been good enough to select as on the whole the most convenient, perhaps I ought to open this discussion; but I must do so more briefly than I should wish, in order to cover duly all points to be considered, as what I have to say would perhaps be more appropriate in the form of a separate paper than in the form of a discussion.

I should premise that in any formula in regard to pile-driving, it must be assumed that the piles are driven under rational conditions, so that they are neither so heavily struck and so neglected in respect to sawing off broomed heads as to be battered and broomed unreasonably at the time the last few blows are given, nor so lightly struck that the blow does no work. It must always be assumed, too, that the pile has been sinking with reasonable regularity under the last few blows, and that the behavior of the pile when driving, and of the other piles around it, has been such as to give reasonable assurance that the apparent uniformity of set is not deceptive, i. e., that the pile is not really on the point of breaking through a thin crust into a semi-fluid substratum, or anything of that kind. Difficulties of that kind must be guarded against by the judgment and experience of the engineer, or not at all. Formulas cannot attempt to provide for them, but, fortunately, they are the exception.

The formula to which Mr. Crowell gives the preference was originally published in Engineering News of Dec. 29, 1888, in connection with an extensive discussion of the whole subject, and in comparison with 16 other formulas. It was there given in the form

$$L = \frac{2wh}{s + 1}$$

in which L = "the safe working load for piles under all ordinary conditions, to be reduced under exceptional conditions (as notably with irregular penetrations), but never exceeded unless the pile is known to rest on rock and act as a column"; w = the weight of the hammer in pounds; h = the height of fall in feet, and s = penetration under the last blow in inches, "assumed to be sensible, and at an approximately uniform rate."

This formula was put forward as a purely empirical one, and its usefulness established only by comparing its results with known instances of resistance, and with the indications of other formulas, but, as a matter of fact, it was not purely empirical by any means; on the contrary, the general form

$$L = \frac{fwn}{s + c}$$

was first deduced as the correct form for a theoretically perfect equation of the bearing power of piles, barring some trifling and negligible elements to be noted; and I claim in regard to that general form that it includes in proper relation to each other every constant which ought to enter into such a theoretically perfect practical formula, and that it cannot be modified by making it more complex, as Mr. Crowell proposes, or by making it less complex, without making it less correct and trustworthy as well as less convenient. The numerous formulas by such high authorities as Weisbach, Rankine, Sanders, Nystrom and many others, which contain from four to six other constants or variables, and have much more complex forms, I claim to be not only practically unsuitable, and for the most part, untrustworthy, but theoretically erroneous; not, of course, in their mathematical work, which I should not venture to question, but in their practical premises. This position I shall not now attempt to establish affirmatively, otherwise than by summarizing the process by which my own formula was deduced, which I believe to leave no gaps open for correction by more minute work. An error of judgment which has unnecessarily and greatly complicated many of the formulas is dealing with the energy of the blow in terms of weight multiplied by velocity, instead of foot-pounds of work.

In any case of pile-driving by blows, the work done is represented by the product of weight of hammer multiplied by height of fall = wh. There is a small loss from air resistance and friction in the guides, but this is infinitesimal with vertical guides, and is universally neglected. Mr. Crowell suggests determining this loss by chronograph observations, but it would be a waste of time. Even with a 30-ft. fall the striking velocity is only 30.1 miles per hour; the mean air resistance to the hammer is two to four lbs., and the loss therefrom merely equivalent to so much off the weight of the hammer, or about 1 part in 1,000. As for friction, that is always a function of pressure, and though the hammer itself is heavy, it can never press with much force against the vertical guides, which it loosely fits, if all is in good order. Even if the guides are not quite vertical, the loss must be small, except in some rare cases when the guides are purposely set much inclined in order to drive inclined piles. Such cases are exceptions not now considered for which a proper special allowance can be made by the engineer.

All these foot-pounds of energy, wh, then, barring this universally and justly neglected fractional loss, are expended somehow during the set s of the pile, so that the mean resistance in pounds to the hammer during that set is expressed by $\frac{wh}{s}$.

If h be in feet, however, and s in inches, this formula takes the form

$$\frac{12wh}{s}$$

Now, the energy of the blow may be absorbed in any or all of these five ways, which we will severally consider:

1. In brooming and mashing the pile, either (a) visibly on the head, or (b) invisibly at the foot of the pile, or even in its middle, which latter is far from uncommon.

2. In bouncing, and thus striking two or more light blows instead of one heavy one.

3. In compressing elastically the material of the pile and hammer.

4. In overcoming the inertia of the pile and the static grip of the earth upon it.

5. In causing the pile to penetrate against the surrounding earth's resistance.

1 (a). Brooming of the head is an enormous source of loss of work, whenever it occurs, both directly and in cushioning the blow. Some such brooming almost always occurs. The recognized remedy against this, however, and an entirely effective one, is to saw off the broomed part, and give a fresh solid surface for the blow, when the pile is nearly home. Don J. Whittemore, M. Am. Soc. C. E., contributed a paper to this Society some years ago, giving the results of some most valuable observations on this head, which should be studied in this connection.

1 (b). Brooming at the foot does not diminish the energy of the blow on the pile, but merely dissipates it unproductively. It can generally, but not always, be detected by the skilled pile-driver by a change in the behavior of the hammer and pile. No formula does or can provide against it. The judgment of the engineer and his assistants must be relied on to detect its probable or actual occurrence, and to act accordingly by

stopping the pile-driving after brooming has begun. If all these precautions be taken, brooming will not occur to any injurious extent to any considerable number of piles. Therefore, no formula does or can make any allowance for its effects other than in the usual coefficient of safety.

2. Bouncing invariably means that all the energy of the blow cannot be utilized in work, either because the pile has struck a solid obstacle to further penetration, which is soon detected, or because the hammer is too light or its striking velocity too great, or both, to get the pile in motion before it reacts elastically with more force than the hammer is exerting to push it down. In many cases the remedy indicated is a heavier hammer. In all cases the height of the bounce, and considerably more, represents so much absolutely wasted energy, which goes to increase the brooming but not to increase the penetrating force, because the energy escapes again from the pile before the latter begins to move. The judicious pile-driver, therefore, will and does cut down the fall at once, when he finds that bouncing occurs to any extent, and usually accomplishes far more with the lighter fall by so doing. A slight bounce at the end of every blow, as we shall see, is an invariable and necessary accompaniment of all good pile-driving.

3. Elastic compression within the limits of elasticity is not a source of loss except to a trifling extent, determinable as follows: it is necessarily greatest at the instant after impact. As the pile gets under way, the elastic compression necessary to transmit from the hammer through the pile a pressure sufficient to cause the pile to penetrate diminishes, but so long as the hammer and the pile together are moving downward this decrease and resulting elastic expansion all takes effect to cause the foot of the pile to move a little faster than the head and the hammer above it. After the energy of the blow is so spent that the pile can penetrate no further, the remnant of elastic compression in the pile can only expend itself upward, and it then causes a slight bounce of the hammer. Except that the speed of expansion is not quite quick enough it would, we may well believe, cause a considerable bounce, as it does in any case at times.

This last remnant of energy is wasted, but it also is small and negligible, except in enforcing the necessity of a coefficient of safety. None of the formulas which nominally take into account the elasticity of hammer and pile really allow for it in this way. Therefore, except for the proviso hereinbefore considered, all that we need to take into account in seeking to determine some measure of the bearing power of piles, is the work done in actually moving the pile. (Items 4 and 5 above.) This I have dealt with as follows:

Let the ordinate os (Fig. 1) = the penetration of any given pile under a blow, and let the rectangle os CB = wh = the energy in foot-pounds of that blow. Then will

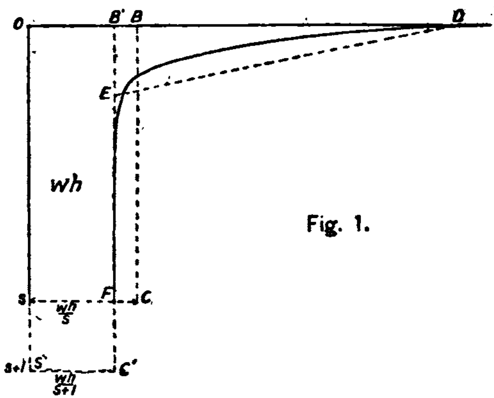

Fig. 1.

the abscissa sC = the mean resistance of the pile during its set. In what manner is that resistance actually distributed, and what part of it bears the nearest relation to the future bearing power of the pile?

So far as the inertia of the pile is concerned, that does not enter into the problem, except as affecting the elastic compression of the pile, which we have already considered. The energy absorbed in acquiring velocity is given out again in surrendering it, and the mean result is the same. What we are after only is the external resistance to the motion of the pile.

In its absolute amount, this is as variable as the earth itself. But reasoning from the general laws of friction and the known nature of earth, these general conditions must obtain: at the instant after impact there must be a very large excess of external resistance, oD (Fig. 1), due to two permanent causes: (1) the excess in the coefficient of static friction or of friction at very low velocities over that at relatively high velocities, and (2), the settling of the earth around and into the irregularities of the pile, in the interval since the last blow. This last, in fact, may be considered as a general phenomenon, which occurs, in some degree, with all surfaces in frictional contact, so that (2) is only a part of (1).

(Under the general laws of friction between such substances, as I understand them, this heavy excess of initial friction, oD (Fig. 1), will rapidly, but not instantaneously, decrease to some point E, where it will have a much reduced value, s'c', which thereafter will remain sensibly constant during the remainder of the set. In this case, we have the irregular figure of oDEFs, whose area must = wh.

The nearest measure of the future bearing power of the pile, obviously, will be the comparatively uniform frictional resistance to penetration, sF (Fig. 1), after the initial excessive resistance has been overcome; because, in large part, this excess is due to the suddenness with which the blow acts on the pile, and a gentler unceasing pressure of much less force in pounds may overcome it; besides which, tremors, seepage of water, yielding of surrounding soil, and other like causes may overcome it. The same causes may partially overcome the smaller constant resistance sF, but that possibility we allow for in the coefficient of safety. All that is claimed is, that this force, sF, comes the nearest to a true measure of future bearing power of all possible constants.

To determine sF in terms of non-variables, we must construct a rectangle os'C'B' whose area = oDEFs = osFB' + DB'E = wh, which I do as follows:

I assume that the decreasing excess resistance outlined by the line ED, and whose value in foot-pounds is expressed by the irregular area B'ED, is confined within the first inch of penetration (i. e., that B'E = 1), and that the initial excess B'D = 3oB' = 3sF. The selection of these particular constants instead of others a little higher or lower is pure assumption, in the sense that we can never know experimentally, or, at least, do not now know just how this is. But it is based on extensive observations of the behavior of piles in driving and on many years' experiment and study as to the general laws of friction, as embodied in part in my paper on that subject (Transactions Am. Soc. C. E., 1884, Vol. XVIII, p. 409), where the diagram of actual observations on page 420 will be found to bear a striking resemblance to Fig. 1 of this discussion. I have no doubt that the above assumptions are essentially accurate and suitable, especially as considerable modifications thereof do not essentially modify results. That the general nature of the distribution of force is correctly outlined in Fig. 1, does not in my judgment admit of doubt.

Under these two assumptions we have geometrically,

$$\begin{aligned} \text{Triangle } B'ED &= \tfrac{1}{2}\, L'D \times B'E \\ &= \tfrac{1}{2}\,(oB' \times 3) \times 1 \\ &= 1\tfrac{1}{2}\, oB'. \end{aligned}$$

But, furthermore, the irregular area B'ED is geometrically equal to about two-thirds of triangle B'ED, whence

$$\text{Irregular area } B'ED = oB' \times 1.$$

Then, in order to determine the value of the abscissa $oB' = sF = s'c'$, we must add to the rectangle oF an area $= oB' \times 1$, which we do by making $ss' = 1$ and $s'c' = oB'$, whence we have, letting $oB' = R =$ the assumed maximum bearing power of the pile—

$$wh = R \times (s + 1);$$

whence we have

$$R = \frac{wh}{s+1};$$

or, if h be in feet and s in inches, as usual,

$$R = \frac{12wh}{s+1}.$$

This was and is my formula for the probable ultimate bearing power of piles. Barring the petty exceptions noted above, I believe it to be incapable of further refinement and amplification in any way in order to express more accurately the probable ultimate bearing power; and I believe it to be especially unwarranted and injurious to tamper with the constant 1, as Mr. Crowell proposes, in order to allow for future conditions of the pile, in respect to tremors, or in respect to the importance of stability. That constant has no relation to such allowances, any more than the variables w, s or h. The proper way to allow for these future differences of conditions, and the only proper way, is by varying the coefficient of safety.

For myself, I assumed the factor 6 as the coefficient of safety, giving to the formula the form

$$S = \frac{2wh}{s + 1}$$

in which S = the safe load in the pile = 1-6 the probable ultimate. I assume 6 as a factor of safety, rather than 4 or 5, simply because I found 6 to give as big loads as are customary, or as are in many cases safe. I do not question that in many cases a factor of 2, 3, 4 or 5, or even 1, might also prove safe. In some cases they have done so, but in other cases they have not; whereas I have as yet discovered no cases where the factor 6 had proved insufficient, either experimentally or in service. As the factor 6, moreover, will in no case require piles to be driven closer together than is customary and reasonable, I should advise in all cases adhering to it, unless under some very exceptional circumstances, where the engineer may see that he has special cause and justification for taking more chances. He can be reasonably sure that his pile will do its allotted work safely with a factor of 6, but not with a smaller factor—that is all.

Apart altogether from the special reasons so far advanced, it is wrong in principle to tamper with the constant 1 and make it a variable, in order to vary the factor of safety to suit future conditions, as Mr. Crowell proposes. That constant is a part of the denominator of a fraction. For well-understood mathematical reasons, if it is desired to increase the value of a fraction by 10, 20, 50, 100 or any other per cent., which is what Mr. Crowell is aiming at, it is impossible to do so in any simple way, by modifying the denominator. It should be done by a factor modifying the fraction as a whole, i. e., multiplying the numerator. When, as in this case, the denominator consists of two terms, any attempt to vary the value of the fraction to suit any desired coefficient of safety, by varying only one of the terms of the denominator, is particularly objectionable.

A further reason why the constant 1 should not be tampered with, is that, as it happens, in the extreme case when $s = 0$, i. e., when the pile has struck solid ground and can penetrate no further, the formulas reduce to the form $R = 12wh$, and $S = 2wh$, which happen to be just about what the pile can safely carry as a column, as ultimate or safe loads, under ordinary and probable values of w and h, whether regarded as a short column with its bearing power limited only by the crushing strength of the wood, or as a long column liable to flexure. Therefore, it becomes unnecessary to consider the special case of the pile acting as a column. The formula is general for all conditions. When the constant 1 is reduced to considerably less than 1, as Mr. Crowell proposes, the apparent safe loads become excessive, and considerably more than the crushing strength of the pile itself. As it is only in these cases that Mr. Crowell's proposed modifications give materially different loads from the original simple form of the formula, it will be seen that the added complexity is not only without advantage, but distinctly injurious.

To prove this fact I have computed the following table, which sufficiently explains itself. The last three columns give the ratio of the safe load, indicated by three cases of Mr. Crowell's modified formula in comparison with my original simple form. The table may be divided horizontally into two main parts, that for penetration of less than 1 inch and of over 1 inch.

Relative Safe Load Indicated by Original Engineering News Formula, and the Same as Modified by Mr. Crowell.

Set S.	Engineering News.	Ordinary cases.	Railway bridges.	Machin'y foundations.
None	1.00	3.08	1.87	1.13
0⅛	1.00	2.08	1.56	1.13
0¼	1.00	1.58	1.30	.97
0½	1.00	1.37	1.18	.93
1	1.00	1.25	1.11	.91
2	1.00	1.07	.98	.88
3	1.00	1.08	.96	.88
4	1.00	.98	.94	.88
5	1.00	.97	.93	.88
6	1.00	.95	.93	.88
7	1.00	.95	.93	.89
8	1.00	.95	.93	.89
9	1.00	.94	.93	.89
10	1.00	.94	.92	.90
11	1.00	.94	.92	.90
12	1.00	.94	.92	.90

Considering the small penetrations first: Mr. Crowell's modifications have substantially no effect on piles for machinery foundations, nor on any piles where the penetration is as much as one-half inch. Less penetrations than that are generally bogus, as practical men know, and indicate that the pile is brooming and mashing rather than penetrating further. For these cases Mr. Crowell's modifications indicate that from one and one-half to three times greater loads are safe, but this is untrue as a fact, as just stated, for the simple reason that such loads amount to one-half to three times the safe strength of the pile as a column.

For penetrations above 1 in., Mr. Crowell's formula gives almost identical results for "ordinary cases" in a much less simple way; but for railway bridges he says, in effect, that my simpler form gives 2 to 8 per cent. too great loads, and for machinery foundations he says, in effect, that my form gives 10 to 12% too great loads. These are small differences to dispute over; but I deny the fact that they exist, or that there is any evidence to show that they exist, or tending to show it. Certainly Mr. Crowell advances no evidence to show that they do. I think he will be surprised to find how little effect upon the final result his apparently considerable modifications of the original simple formula really have. Before proposing them, evidence should be advanced to show that the simpler formula is really the less trustworthy of the two in some one case, at least; and, assuming that evidence to have been produced, the proper way to give it effect is to make the coefficient 2 of the numerator a variable and not the constant 1 of the denominator.

I must not be understood to take the position that the load placed on piles should not be decreased in important structures subject to tremor, or that it may not be increased for carrying unimportant temporary structures. I merely say that any excess or deficit in such cases is guesswork, pure and simple, and therefore does not belong in a formula. The way to make such changes is to space the piles a little nearer together or farther apart than we otherwise would; not to "monkey with" our basic formula (which is already as exact as theory permits us to make it) by arbitrary changes in the general direction of the allowances we wish to make.

Mr. John C. Trautwine, Jr., after briefly commenting on the inherent difficulty of securing any precise formula of general application, presented the following discussion, an exceedingly valuable feature of which was a big list of actual records of the bearing power of piles:

The weight of ram and the height of fall may indeed be determined with reasonable exactness, and the product of these gives us, no doubt, quite approximately, the energy stored in the ram at the instant when it comes into contact with the head of the pile; but in estimating how much of this energy is utilized in driving the pile, we are obliged to remember that the mass of the pile has yet to be set in motion; that the direction of the blow can seldom be more than approximately in line with the axis of the pile; that the vibration of the pile under the blow will vary with the length of the pile projecting from the ground; that according to circumstances this vibration may facilitate or impede the driving, and that to an unknown extent; that the pile, even at its best estate, is more or less compressible, and that the head must become more or less crippled by the blows delivered upon it, thus further increasing and rendering still more uncertain the amount of the useless consumption of energy in the delivery of the blow.

But perhaps the most serious difficulty is encountered when we come to deduce the supporting power from the estimated effective energy of the blow, dividing the latter by a quantity containing the penetration or set per blow, as is done in all the formulas embraced in the present discussion. As observed by Mr. Rudolph Hering,* "the only method which can be depended on in calculating the sustaining power of piles held by friction, is the experimental one which introduces the actual distance (s) which a pile sinks under the last blow." And yet this very factor, the absence of which would render these formulas irrational and without which they would fall to the ground, constitutes at the same time, perhaps, their weakest point, especially in formulas which, like Major Sanders', have not a

* Given elsewhere in this volume.

second additive quantity in the divisor. The penetration, as compared with the height of fall of the ram, is in most cases very small. The circumstances of actual practice seldom permit an accurate measurement, even of the apparent penetration, which again is always complicated to a considerable and uncertain extent by the compressibility of the pile and of the soil, and by the brooming of the head of the pile. And yet a very small error in the measurement or estimation of the penetration evidently causes a wide divergence in the results given by any formula in which this factor performs a prominent part.

Finally, we are almost entirely without experimental knowledge of the subject. All of the results I have been able to obtain in which the ultimate load is given or from which it may be inferred, are embraced in the handful mentioned below, and some of these (as explained in place) are of an exceedingly doubtful character.

But, the uncertainties of the case do not cease with the driving of the pile. Vibrations due to the load itself or to those upon neighboring structures, the lubricating effect of infiltrating streams of water, the reduction of pressure by the dredging away of material from adjoining works; these, and perhaps other causes, may operate to reduce the frictional resistance of the pile.

The author has earned the thanks of the profession by endeavoring to reduce the element of uncertainty attending pile-driving operations. He has done this by selecting that one of the existing formulas

$$\left(L = \frac{2wh}{s+1}\right)$$

which most commends itself to him by its simplicity and by its conformity to known principles, and has modified it by changing its divisor $(s+1)$, substituting first the expression $s+0.3$, and finally the expression $s+0.1+n+n'$, in which $n =$ half the square root of the penetrations under a standard blow of 40,000 ft.-lbs., and n' serves the purpose of an additional factor of safety and varies from 0.1 to 1 according to the duty to be performed by the structure.

The five formulas discussed by Mr. Crowell may be written thus:*

$$\text{Sanders:}^{**}\ L = \frac{1}{8}\,\frac{12wh}{s}^{***}$$

$$\text{Wellington:}\ L = \frac{1}{6}\,\frac{12wh}{s+1}^{***}$$

$$\text{Crowell (a):}\ L = \frac{1}{8}\,\frac{12wh}{s+0.3}^{***}$$

$$\text{Crowell (b):}\ L = \frac{1}{8}\,\frac{12wh}{s + 0.1 + \frac{1}{2}\sqrt{s\,\frac{40,000}{wh} + n}}^{***}$$

$$\text{Trautwine:}\ L = (\tfrac{1}{2} \text{ to } \tfrac{1}{12})\,\frac{50w\sqrt[3]{h}}{s+1}$$

in which, as in Mr. Crowell's paper,

L = the safe load on one pile;*
w = the weight of the ram;*
h = the height of the fall in feet;***
s = the penetration per blow under the final blows, in inches;***
n' = a term varying from 0.1 to 1.

As thus written, the numerical fractional coefficient is the factor of safety, and the other factor is the extreme load R on one pile.

It will be noticed that there is a certain similarity of form existing between all of these formulas. All have in the numerator the product of the weight w of the ram by a function of the height h of fall, and in all but ours this function is the fall h itself. They thus agree in deducing, more or less directly, the work done from the energy stored in the ram, without making any definite provision for the inertia of the pile; resembling in this the simplest possible rational formula:

$$R = \frac{12wh}{s},$$

in which R is the resistance (assumed to be constant) of the earth to the penetration of the pile; in other words, the extreme load of the pile.

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* L and w to be measured in one and the same unit, as both in pounds or both in tons.

** Mr. Crowell ascribes this formula to Weisbach, but I do not find it given by that author. It is given by Major John Sanders in the "Journal of the Franklin Institute," November, 1851, p. 304.

*** If h and s are taken in one and the same unit, as both in feet or both in inches, the number 12 disappears from the numerator of the first four formulas.

Like this very simple formula, also, all of those discussed contain in their denominators the penetration, s, of the pile under the last blow, or, as it is often put, the penetration per blow under the last few blows; but, in all except that of Major Sanders, the denominator contains a second term to be added to the penetration, and in Mr. Wellington's formula and our own this added term is simply 1 in.

Mr. Crowell refers to the use, in our formula, of the cube root of the fall as being theoretically illogical and practically inconvenient. Inconvenient it certainly is, as compared with the use of the fall itself. but I do not see that it is "theoretically illogical." On the contrary, so long as increase of height fall beyond moderate limits is found to be attended by increased losses of energy, it must be theoretically logical to make allowance for them, and the simplest if not the most rational way of doing this would seem to be, to represent the energy of the blow as varying with some power of the fall lower than the first.

Other things being equal, a high fall seems to cause a greater waste of energy in damaging the pile, and, as Mr. Wellington has pointed out, in rebounding of the ram, besides allowing a longer time for the material around the pile to re-compact itself.

McAlpine's experience at Brooklyn led him to believe that the supporting power of a pile varies as the square root of the fall.

It can readily be shown that the large coefficient (50) necessitated by our use of the cube root gives excessive loads in cases of very low fall, such as may perhaps occur at times with the Nasmyth steam-hammer pile-driver. Thus, for a fall of only 1 ft., our 50 $\sqrt[3]{h}$ becomes 50h, and may thus give a load even much greater than

$$\frac{12wh}{s}$$

(see Fig. 2). For a 2,000-lb. hammer falling 1 ft., and producing 1.5 ins. penetration, our rule gives 40,000 lbs. as the extreme load, whereas the greatest theoretical extreme load

$$\frac{12wh}{s},$$

is only 16,000 lbs. It may be proper to consider, however, that such cases hardly come within the actual probabilities of pile-driving, and these alone our formula was intended to cover. Indeed, I have no doubt it was constructed by its author as a rule of thumb by making it fit such experimental cases as came within his observation, and it is safe to assume that none like the one supposed were encountered by him.

Whatever may be thought of Mr. Wellington's demonstration of the correctness of the additive term 1 in the divisor of his formula and in that of ours, the omission in Sanders' formula of any such term must, I think, be regarded as a fatal defect, for it makes that formula give excessive loads for very small penetration, and infinite loads in cases where no penetration can be detected, and this no matter how light the ram or how low the fall. This, of course, is theoretically correct. A pile which undergoes absolutely no set under a blow from a falling feather will theoretically support the universe, but a formula which would make it do so in practice is hardly applicable to cases of very small penetration. It is but just to Major Sanders to note that in proposing this formula he limits its application to cases where the pile "meets such an uniform resistance as is indicated by slight and nearly equal penetrations for several successive blows of the ram." This rules out cases where the observed penetration is 0, but still admits those where the penetration is very small and where the safe load by the formula is therefore excessively great, as indicated in Fig. 1 herewith.

It has always been my impression that the "1" in the divisor of our formula was simply an empirical term used by the author to avoid the difficulty just referred to, and that he arrived at its value by trial with recorded cases.* Mr. Wellington's claim that it can be shown to be logically correct and a necessary factor in any rational formula, was, therefore, an agreeable surprise to me, and I have read with much interest his argument in the premises.

But, although I am naturally willing to be persuaded of the soundness of this position, I am obliged to con-

* In presenting his formula, he remarked: "Although this is all wretchedly empirical, it certainly appears to accord moderately well with such facts as we have been able to obtain. Like other rules of this kind, however, it should be used with caution; and with a wide margin for safety in important cases."

fess that the perusal has not resulted in that firmness of conviction which could have been desired. It seems perfectly reasonable to assume that there is, as Mr. Wellington claims, an excess of resistance at the beginning of penetration; but we are not shown how the values of B'D and B'E in Mr. Wellington's Fig. 1 (B'E = 1 in., and B'D = 3.OB') are deduced from his observation of the behavior of piles, and from his experiments and study as to the laws of friction, and in the absence of this I am inclined rather to indorse his admission that the adoption of these values "is pure assumption, in the sense that we can never know experimentally, or at least, do not now know, just how this is."

Hence, I cannot join in Mr. Wellington's objection to Mr. Crowell's innovation in "tampering with the constant 1, and making it a variable." On the contrary it seems to me altogether probable that this term may, in fact, vary greatly (perhaps as much as from 0 to 2, 3 or 4 ins., or even more) with differences in the character of the soil and of the pile, or in the weight of ram and height of fall, and should, therefore, be made to appear as a variable in the formula. Indeed, if we had at command a sufficient assortment of reliable experimental data, I think we might be able, by modifying this term, to produce a more nearly serviceable formula than any yet presented. Mr. Crowell's proposed innovation, therefore, so far from being an unpardonable sin, seems to me to be an effort in the right direction, although a comparison of his results with the few experimental data at hand seems to indicate that he has not yet hit upon just the happiest combination.

It appears to me also, in view of "the excess in the coefficient of static friction, or of friction at very low velocities over that at relatively high velocities," that Mr. Wellington's diagram should show an increase of resistance toward the end of the penetration, where the pile is being brought to rest, and where, consequently, the velocity is rapidly decreasing. This final excess of resistance, would, no doubt, be less than the initial one (B'ED); but, such as it may be, it would seem sufficient to render us cautious in accepting implicitly an argument based upon the diagram without it.

Mr. Crowell, in his first suggested modification of Mr. Wellington's formula, proposes substituting 0.3 in place of 1.0 in the divisor. That this is an unfortunate deviation in the direction of Major Sanders' omission of any additive term, is indicated by my Fig. 1, where the curve representing this form of Mr. Crowell's formula is seen to mount very rapidly as the penetration becomes less than, say, 1 inch. Mr. Crowell's final formula, in which this term becomes

$$0.1 + \frac{1}{8}\sqrt{s\,\frac{40{,}00}{wh}},^*$$

suffers even more severely from this defect, for the additive term here diminishes with the penetration. While we may not unquestioningly accept Mr. Wellington's argument in behalf of the constant value "1" for this term, these considerations certainly indicate that it is, at least, safer than Mr. Crowell's proposed modifications.

I am inclined to question the propriety of allowing the factor n to be determined by means of a standard blow of 40,000 ft.-lbs., as in Mr. Crowell's formula, without restriction as to weight of ram or height of fall. It sometimes happens that a pile refuses under a light ram with high fall, but moves satisfactorily with a heavy ram and low fall, and sometimes the reverse of this obtains, perhaps, chiefly in cases where a hard and shallow stratum is encountered.

It will be noticed that in all the formulas, except Mr. Crowell's (b) and our own, the value of the factor of safety is fixed. In ours "not more than one-half the extreme load" is to be taken "for piles thoroughly driven in firm soils, nor more than one-sixth when in river mud or marsh"; while, if there is liability to tremors, only one-fourth and one-twelfth of the extreme load are to be taken respectively. Mr. Crowell has undertaken to provide, in addition to his fixed factor of safety of one-sixth, a sliding scale for the term n' in the divisor of his formula, whereby that term is given a series of fourteen different values, de-

*Inasmuch as the term n' of Mr. Crowell's final formula serves the purpose of a factor of safety, and varies according to an arbitrary scale, with the use to which the superstructure is to be put, it should not, I think, be included here.

pending upon the service for which the superstructure is to be used and upon the exposure to which it is to be subjected.

In view of the great diversity of the conditions under which piles are driven and of those under which they are subsequently employed, I cannot but think it better to have an elastic factor of safety rather than one which remains the same whether the superstructure is to be on the one hand a lumber yard or a mausoleum, or, on the other hand, a trestle or a drawspan to be used by trains of all descriptions.

It would appear, therefore, most desirable to provide a series of factors for safety, arranged, like Mr. Crowell's, to suit the various conditions of service; but, until the experimental data at our command become vastly more numerous and more reliable than they now are, any such table must, as already intimated, be taken, like the "1" in the divisors of Mr. Wellington's formula and of our own, as a "pure assumption." In the present state of our ignorance, much must be left to the judgment of the engineer, and he may well be thankful if we succeed in concocting a rule of thumb which gives results bearing some sort of proportion to the probable extreme load, leaving it to him to decide what portion of this load he will take his chances with.

Comparing, then, the Trautwine formula as it appeared in the first and later editions, we find that in the former we have: Extreme load in pounds =

$$\frac{60 \times \text{weight of ram in pounds} \times \sqrt[3]{\text{fall in feet}}}{\text{penetration in inches} + 1}$$

with factors of safety from one-half to one-third, and that in the later editions the coefficient has become 50 and the factor of safety from one-half to one-twelfth.

Hence, Mr. Crowell's presentation of our formulas in his Diagram 2, while correct as far as it goes, is not sufficiently comprehensive to represent our formula properly, for his upper curve represents it with a coefficient of 60, and a factor of one-half, while the lower one represents it with a coefficient of 50 and a factor of one-third. A satisfactory showing would require, in each of his four diagrams, at least four curves for our formulas, viz., two with a coefficient of 60, one of them with a factor of one-half, the other with a factor of one-third; and two with a coefficient of 50, one of them with a factor of one-half, and the other with a factor of one-twelfth, and I therefore submit herewith (Fig. 1) diagrams for his two extreme cases, I. and IV. (h = 15 ft., and h = 30 ft., respectively), drawn in accordance with this suggestion.

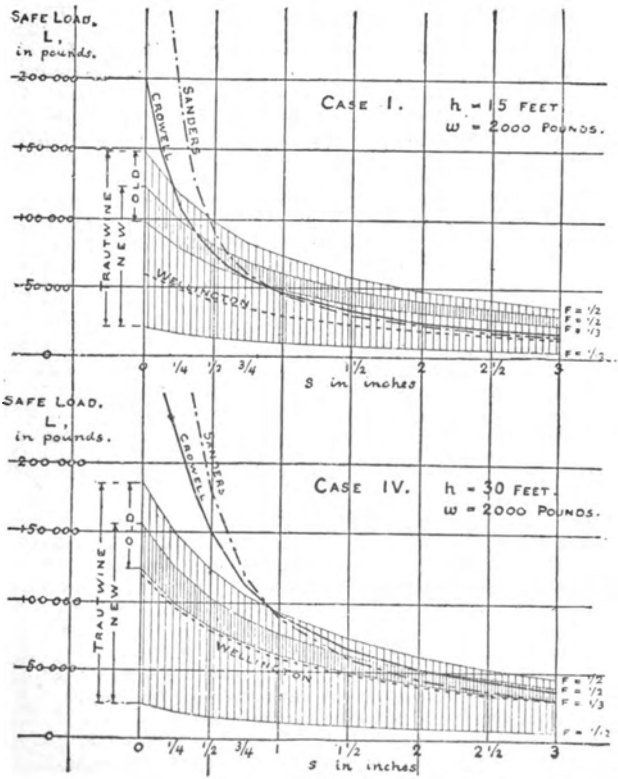


FIG. 1.

In these diagrams I have used lines of the same characters as those used by Mr. Crowell, to designate the Sanders, the Wellington and the Crowell (a) formulas, respectively, each of which, allowing no latitude as to the coefficient of safety, is properly represented by a single curved line, while our formula, in its two forms, each with a variable factor of safety, is properly represented by shaded areas.

These diagrams show clearly the defect of the Sanders formula, already referred to, the allowed load rapidly approaching infinity as the observed penetration falls below three-fourths and one-half inch, and they also indicate, I think, that Mr. Crowell's proposed substitution (a), of 0.3 for 1.0 in Mr. Wellington's formula, errs in the same direction.

The resemblance between Mr. Wellington's formula and our own is shown by these diagrams, each of which represents a constant height h of fall; Mr. Wellington's formula falling well within the very wide area embraced between the limits of our later form, and necessarily partaking of its character. But lest it might be hastily assumed, in view of this, that Mr. Wellington's formula was but an imitation of ours, I submit also a second diagram, Fig. 2, in which the penetration s (assumed at 1 in.) is supposed to be constant, while the fall h is made to vary.

Plotted in this way, the formulas of Sanders, Wellington and Crowell (a) are necessarily straight-line formulas, as is also the theoretical formula.

$$\text{Extreme load} = \frac{12\,wh}{s}$$

which I have added here for comparison; while our formula, of course, appears as a curve determined by the presence of the cube root of h in its divisor. It will be seen that with a penetration of 1 in. Mr. Crowell's formula (a) gives results almost identical with those of Major Sanders' formula. This diagram exhibits also the fact, already noticed, that our formula, owing to its employing the cube root of the fall, gives excessive loads for very low falls.

It is an ominous fact that neither Mr. Hering in his pamphlet, already quoted, nor the author, in the present paper, brings forward any results of experiments in support or in refutation of any of the formulas;

ominous because it indicates the dearth of such results. For years I have been on the lookout for data of this kind; but the result, as embodied in the following table, is discouraging in the extreme. I cordially second the hope of the author, "that in the discussion which this paper may call out, practical examples will

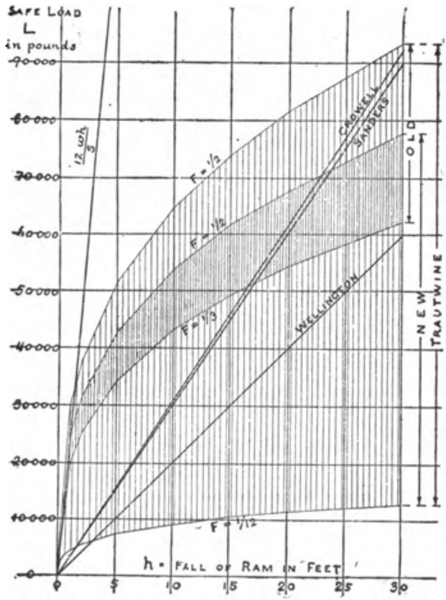


FIG. 2

be given, taken from the actual behavior of piles in service, under loads of various character."

When only the actual safe load is given, we are left in doubt as to how much the pile would safely bear. Hence, I have restricted my list of results chiefly to those which give, or from which we may infer, the ultimate or extreme load which causes settlement of the pile, and which our author rather unfortunately calls "the sustaining power" of the pile. I have omitted cases where the piles are known to have failed by being pushed over laterally by the pressure of adjoining arches, or through similar causes other than the vertical pressure of the load upon their heads.

Mr. Trautwine then gives many pages of detailed records of bearing powers, which appear in the next succeeding article. The remaining discussions contributing new facts to the record were as follows, omitting parts of the discussions not relating to those facts:

J. Foster Crowell—In reference to Mr. Trautwine's intimation that in most cases there would not be very low falls, I will state that the average stroke of a Nasmyth steam hammer in ordinary use would be from 2½ to 3½ ft.; in ordinary circumstances, the weight of ram is, say, 5,500 lbs. If we take this weight with the full stroke, 40 ins., there would be developed a blow of 18,315 nominal ft.-lbs.; now, if we were to take a hammer of 2,000 lbs. and divide this value by the 2,000 lbs., we would find that we would require a fall of 9.16 ft. to produce the same blow, neglecting resistances in each case. Now, applying the Trautwine formula (later form) in the first case, you will find we obtain 70,368 lbs. as maximum load, but in the second case only 35,838 lbs., or just about one-half; that shows that this objection to the cube root is not a theoretical objection when the steam hammer is used, and I think those who have occasion to drive many piles will make more use of the steam hammer in the future than in the past.

G. Bouscaren, M. Am. Soc. C. E.—I think the trouble about applying a formula to pile-driving is that, in doing so, we gage the resistance of the soil from the penetration of the pile while it is being driven. It often occurs that the resistance of the soil is greater when the pile is being driven than it is after the pile is driven, and vice versa. Here are some examples which occurred in my practice:

In driving piles for trestles for railroads through Illinois, I had to adopt the rule to stop the pile-driving at the penetration of 1 in.; the hammer weighed from 1,800 to 2,200 lbs.; the fall was about 25 ft. I generally found the rule to work very well.

When I came to build a railroad in Louisiana through the swamps of Lake Pontchartrain, I found that the penetration of a 65-ft. pile under the last blow of a 2,500-lb. hammer, falling 25 or 30 ft., was from 9 to 12 ins. Putting two of these piles, one on top of the other, and having a total penetration of 120 ft., the penetration under the last blow was still 9 ins. I thought I would see what the penetration would be if I gave the pile a rest, and I stopped the driving about 25 minutes after the pile had gone in about 40 ft.; the first blow of the hammer, when the driving was resumed, gave a penetration of 1½ ins. I concluded in this case not to consider the penetration under the last blow, but to use piles from 60 to 70 ft. long. About 22 miles of trestle-work were built that way, and none of the piles ever settled.

Here is a case which is the opposite: I built a pile trestle across what was then called the "Slough," back of Bloody Island, in East St. Louis. It was built with three pile bents, the penetration there was from 2½ to 3 ins., less than one-third of what it was in the case of the Lake Pontchartrain trestle, and within two weeks after the bridge was opened, we could not get a train over it; it had settled irregularly from 1 to 2 ft. That was in 1867, when locomotives were much lighter than they are now.

It is often impossible to tell, without actual experience, what reliance can be placed on the resistance of the soil as evidenced by the penetration of the pile.

C. Wheeler Durham, M. Am. Soc. C. E.—In 1870 I was engineer for the Chicago & Northwestern road, in charge of the extension of the line from Madison to the Mississippi River, at La Crosse. One part of the line crossed a marsh in which there was a stream of perhaps 30 or 40 ft. in width, requiring about 800 ft. of bridging. The piles were ordered 45 ft. in length. When we came to drive them, the piles went down to within a foot of the surface without a blow of the hammer at all, they were simply pushed down by the hammer resting upon them. We saw that these 45-ft.

piles would not answer the purpose, so we stopped operations to get a new lot of longer piles. I forget exactly the circumstances which caused us to try these piles a second time in a day or two, but we found then that they did not budge under a fall from the full drop of the hammer; it would not stir them at all. So we pushed the balance of those piles down in the marsh for the 800 ft. of distance, capped them and built trestle-work upon them, and I suppose they are carrying the Chicago & Northwestern road to this day.

L. M. Haupt, M. Am. Soc. C. E.—I think it might be of interest to the members to know how piles were driven in this vicinity even without a hammer. On the Eastern Shore it is the practice in building small wharves for the fruit trade and light-draft steamers, to take the trees of the neighboring forests, and, after erecting a temporary staging with a projecting cantilever upon which two darkies can stand, a pile is placed between them, and is rocked to and fro, its toe resting on the bottom, until by its weight and swaying motion, it beds itself to the required depth. Any cessation of the movement causes the sand to settle and pack around the pile so quickly that it is impossible for the men to start it again. In this way the work is done very cheaply and efficiently, with an inexpensive plant. In the cases cited by Mr. Bouscaren, I think, possibly, the firmness of the piles in the Louisiana swamps is due to an under stratum of sand which settles around and clamps them in place. In the other case mentioned, back of St. Louis, there must have been some mud which was easily moved by a current. I should be pleased to know more about the sections through which they were driven.

William P. Craighill, M. Am. Soc. C. E.—I have just been informed of a peculiar case of pile-driving that occurred in some work in charge of a friend of mine who was improving the Caloosahatchee River, in Florida, where he had to drive piles, and had no pile-driver; the piles were of a kind that would not last long under the blow of a ram. The situation was peculiar; he disposed of it in the following way: Fortunately, he had a very fat man in his party, so that after placing the pile on end, he put this fat man on top of the pile; this gave the first motion to the pile. In order to keep up the interest in the subject, he got two or three men to shake the pile vigorously and try to shake the man off. That was the amusing part of the operation; they shook the pile and the fat man clung on. Fortunately, there was a water-jet available, so that with all these contrivances the piles were carried down to the rock, but I should like to know in the next edition of the formula the form it would take to cover that case.

W. M. Black, M. Am. Soc. C. E.—I cannot tell you very much about the bearing qualities of piles, but I would like to invite the attention of the Society to the lack of formulas and data regarding the safe load for piles sunk by the water-jet. This method of sinking piles is coming more and more into use. It has been used for many years by the United States Government Engineers in their work, and is now used quite generally in sandy soils all over the country.

Some years ago iron screw piles were used in the Government Pier. at Lewes, Delaware. In attempting to screw them down into position the friction was so great that several were broken by torsion. A water jet was then applied to the top surface of the screw blades, and the sinking was successfully accomplished.

The "live-load method" of pile-driving in the Caloosahatchee River, as described by Colonel Craighill, proved very effective. From 150 to 170 piles were sunk daily to a depth varying from 4 to 6 ft. in the sand, by the aid of a water-jet. These could not have been driven by the ordinary method, even had the necessary plant been available.

In Southern waters special precautions are necessary with pile work to avoid the ravages of the teredo. One plan is to use wood which they attack but little. In Florida, the palmetto is extensively used for this reason. As is well known, this wood has a hard shell and soft interior, like a cornstalk, it will not bear a heavy blow from a hammer. In one case palmetto piles had to be sunk to a depth of from 12 to 15 ft. through hard sand. This was done successfully by the water-jet, aided by light taps from a hammer. A slight protection was given to the point of the piles by sheet iron. The pile to be sunk was raised to position, and the hammer placed on it. The water-jet was then applied. When the descent of the pile became too slow, a light blow was given by a hammer fall of 3 to 6 ins. The pile was given a slight motion of vibration, and the pile and the water-pipes were kept moving constantly to prevent the sand from closing in and holding them. This seems to me an important point in pile-driving which has not been much touched on in this discussion—the necessity for keeping the pile moving.

In using the water-jet, we found it necessary to have the quantity of water ample. In fact, we found the essential to be quantity rather than velocity. The velocity had to be sufficient to cause the water to penetrate the sand below the foot of the pile, and make it "live" or "quick," and the quantity so great that the water had to escape by rising along the skin of the pile, preventing surface friction.

In the surveys of the harbors of St. Augustine and Key West, borings had to be made through the sand, to depths varying from 12 to 30 ft. This was done by means of the water-jet, and the method adopted illustrates its action. In compact sand a 2-in. pipe was coupled to the discharge pipe of a hand-pump, and forced down to a depth of from 5 to 10 ft. When it was stopped by the sand closing in on it, a 1-in. pipe was coupled in its place, lowered through the larger pipe and forced down to the required depth. The water rose along the surface of the small pipe, and through the annular space between the two pipes, bringing with it samples of the strata of sand penetrated. Thin strata of shell gravel were also bored through by this apparatus.

Charles Warren Hunt, M. Am. Soc. C. E.—At the pier at Lewes, Delaware, of which Captain Black has spoken, the piles were of solid wrought iron, from 22 to 45 ft. in length, and from 5¼ to 8 ins. in diameter, with cast iron screws 2½ ft. in diameter. When the work was in an experimental stage, the attempt was made to screw down the piles into compact sand with the aid of a jet of water forced between the flanges of the screws to the under side of the flanges. This was not successful, several of the piles being broken by torsion. An inspection of the screws developed the fact that the greatest friction was on the upper surface of the flanges, and it was found that, when the jet was applied to the latter, no more difficulty was experienced, and all the piles in the pier were placed in that way.

The gain by the use of the water-jet on these screw-piles was measured mechanically, and was stated in the report of the Chief of Engineers,* as follows: "That 9-10 of the total pressure on the rope which connects the power with the resistance at once disappears, in effect, on the application of the water-jet."

(A number of discussions relating to pile-driving by water jets only are here omitted.—Ed.)

F. P. Davis, M. Am. Soc. C. E.—I had occasion to drive some piles through very hard, compact sand, where it would take 200 blows of the hammer, falling from 20 to 30 ft., to drive the piles 20 ft. I have seen the piles stick, the water still being applied. By giving a light blow with the hammer the pile would take a sudden start and go from 4 to 5 ft., showing that the sand had been scoured out. I am satisfied the water-jet will scour the sand to quite a depth below the bottoms of the piles.

G. B. Nicholson, M. Am. Soc. C. E.—In the year 1883 I set up a turntable on a pile foundation in the lower part of the City of New Orleans, 2,300 ft. from the bank of the Mississippi River, for the New Orleans & North Eastern Railroad. As is generally known, the soil of that region is a compressible, wet alluvium, making the use of piles for the support of the pedestal of a turntable the best form of foundation.

The turntable I allude to was of the ordinary wrought iron type, and 54 ft. long. The pedestal was supported on a foundation of six yellow pine piles, freed from bark, 10 ins. in diameter at the small end and 14 ins. at the large end. The piles were capped with a grillage of two tiers of 12 × 14-in. creosoted yellow pine, and secured to the piles and to each other by 1-in. drift-bolts. The pedestal of the turntable was bolted on the top tier of timber. Experience in driving a large number of piles in the vicinity a short time previously had given me a great confidence in

* Report of Chief of Engineers, 1873, p. 860.

the sustaining power of piles having a rather large penetration, or sinking at the last blow of the ram.

The record of the pile-driving is as follows:

Length framed.	Set last blow.	Fall of ram.
Ft.	Ins.	
35.5	12	35
34.5	12	30
27.5	12	35
30.	9½	30
29.5	18	35
27.5	9½	32

Weight of ram, 2,825 lbs.; number of blows, 25 to 30; weight of turntable complete, 32,400 lbs.; weight of grillage on top of piles, 3,700 lbs.; weight of engines, with tenders, using the turntable, from 116,000 to 156,-000 lbs.—50% at present are 155,000 lbs.; approximate average daily use of turntable by engines and tenders since building, 13 times. The turntable has been in existence on its original foundation, without repairs, for nine years, and no appreciable settlement has been discovered.

It is a well known fact that if a pile is allowed to est after being partially driven, and the driving resumed after a considerable interval, that the first penetration in the new driving will be considerably less than the last penetration, when the driving was stopped. I do not know what the ratio is in dry soils; but I have several illustrations for pile-driving in the wet alluvium about New Orleans, as follows:

Weight of ram. Lbs.	Fall of ram. Ft.	Penetration before resting. Ins.	Interval of resting. Hours.	Record of driving after resting. Penetration in inches, fall of ram in feet.
2,750	27	7¼	48	$\frac{0}{17}$ $\frac{1}{17}$ $\frac{1}{17}$ $\frac{1}{17}$ $\frac{1}{17}$ $\frac{1}{17}$ $\frac{1}{17}$
3,000	35	6	24	$\frac{1}{20}$ $\frac{1}{20}$ $\frac{2}{20}$ $\frac{4}{30}$ $\frac{6}{35}$ $\frac{6}{40}$ $\frac{6}{40}$ $\frac{8}{40}$ $\frac{8}{40}$ $\frac{7}{40}$
3,000	20	6	12	$\frac{1\frac{1}{4}}{15}$ $\frac{2\frac{1}{2}}{20}$ $\frac{2\frac{1}{2}}{20}$ $\frac{3}{20}$ $\frac{3\frac{1}{2}}{20}$ $\frac{3\frac{1}{2}}{20}$ $\frac{5}{25}$ $\frac{5}{25}$ $\frac{3\frac{1}{2}}{20}$ $\frac{3\frac{1}{2}}{20}$
3,000	18	7	1	$\frac{6}{35}$ $\frac{5\frac{1}{2}}{30}$ $\frac{3\frac{1}{2}}{25}$ $\frac{6}{22}$ $\frac{6}{22}$ $\frac{6}{22}$
3,350	18	7	48	$\frac{1\frac{1}{2}}{20}$ $\frac{2\frac{1}{2}}{20}$ $\frac{2\frac{3}{4}}{20}$

Note.—The expressions in form of fractions mean that upper figures represent penetrations of pile in inches, and lower figures the fall of ram in feet.

It may not be out of place here to call attention to erroneous results obtained in pile-driving, according to a method common in the Southwest—that is, the practice of never detaching the ram from the line. Two or three turns of the line are made on the drum of the winch, and when the desired height is reached the line is slacked on the drum and the ram falls, carrying the line with it.

The braking power of the pulley at top of pile-driver frame and on the drum of the winch, and the consequent loss of momentum of the ram is illustrated by the following experiments.

First.—A pile penetrating 0.5 ft., with a 40-ft. fall of a 2,470-lb. ram, with the line attached to ram and slacked on the drum, penetrated 0.7 ft. with a 40-ft. fall when the ram was allowed a free fall by putting the line at the top of the leads.

Second.—A pile penetrating 0.7 ft., with 45-ft. fall of 2,750-lb. ram, with line attached to ram and slacked on the drum, penetrated 0.9 ft. when the ram was allowed a free fall by cutting the line.

Third.—A pile penetrating 0.32 ft., with 46-ft. fall of 2,500-lb. ram, with line attached to ram and slacked on drum, penetrated 0.40 ft. when ram was allowed a free fall by cutting the line.

THE ACTUAL RESISTANCE OF BEARING PILES.

(From Engineering News of Feb. 23, 1893.)

The following gives a summary of 17 different records of the actual bearing power of piles, as collected by Mr. John C. Trautwine, Jr., for his discussion of Mr. Foster Crowell's paper on "Uniform Practice in Pile Driving" (Eng. News, Oct. 27, 1892, Trans. Am. Soc. C. E., August, 1892). It is doubtless one of the most complete records of such data in existence, albeit in many cases, not to say most cases, the data are open to more or less suspicion as to their accuracy.

We give the statement of conditions in each case in Mr. Trautwine's own words, omitting his reference to authorities, which can be found if desired in the original paper. Below each of these statements we give the safe load indicated by the so-called "Engineering News" formula, viz.:

$$\text{Safe load} = \frac{2\,wh}{s+1}$$

in which w = weight of hammer by any unit (the load given being in the same unit) and h = its fall in feet; s = set under last blow in inches.

Mr. Trautwine himself gave a tabular comparison of the ultimate loads given by three different formulas when applied to these records, viz.: 1. The Engineering News formula. 2. The same in the modified and more complex form proposed by Mr. Foster Crowell. 3. The Trautwine formula. We do not summarize this comparison, first, because it clearly shows that the Engineering News formula gives the closest approximation of the three, and secondly, because the Engineering News formula for ultimate load (= six times the safe load) is not intended to be used for determining ultimate loads, and not alleged to give them with any accuracy, for the reason that the ultimate load is a much more variable quantity than the permanent safe load. At least we so understand it; and certainly the safe load is the only thing we are aiming to determine or care to know. If, therefore, formulas are to be compared, the only proper way is to include the effect of their proposed factors of safety, which, for the Trautwine formula, are 1-12 to 1-2.

To show the effect of doing so we may instance seven cases of known loads and facts as to driving which are given in Trautwine's "Pocket-Book," and are an addition to the following list. It should be borne in mind that in some, if not all of the following instances of piles under foundations, the surrounding soil bears an unknown proportion of the load, so that the load actually coming on the piles may be several times less than stated.

Instances of Bearing Power of Piles given in Trautwine's Pocket Book.

Locality and soil.	Hammer, fall and set.	Actual load.	Safe load by Eng. News.	Safe load by Trautwine's formula.
Chestnut st. Br. Mud.	1,200 lbs., 40 ft. ¾ in.	40,300	29,100	8,000 to 48,000
Neuilly Bridge. Gravel.	2 000 lbs , 5 ft. 0.016 in.	105,300	19,700	14,500 to 87,000
Hull docks..... Mud.	1,500 lbs., 24 ft. 2 in.	45,000 to 56,000	24,000	6,180 to 37,100
Royal Border Bridge........ Sand and gr.	1,700 lbs., 16 ft. 0.05 in.	156,800	53,700	17,580 to 105,500
Phila. expts.... Soft mud.	1,600 lbs., 36 ft 18 in.	11,560 to 20,120	6,060	1,194 to 7,165
U. S test pile.. Silt and clay.	810 lbs., 5 ft. 0.375 in.	59,600	6,600	4,858 to 29,150
French rule ..	1,344 lbs., 4 ft. No set.	56,000	10,742	6,575 to 39,450

It will be seen that the last column gives extremely vague indications as to the real bearing power. Of what use would be a formula which simply told a man that the proper cost of a structure was from $8,000 to $48,000, while the utmost it could cost without breaking the company ought to be about $96,000, but might be a good deal more or less? That is what the last column of the above table says in effect, with the further evil feature that it encourages a man to believe that he may spend up to $48,000 and still have a "factor of safety of two," when the fact is he cannot do anything of the kind.

No formula can attempt to state exactly how much should be spent in such a case, or how much load can safely be placed on the pile. What the Engineering News formula does purport to do is to set a definite limit, high enough for all ordinary economic requirements, up to which there are no records of pile failures, excepting one or two dubious cases, where a hidden stratum of bad material lay beneath the pile, and above which there are instances of both excess and failure, with an increasing proportion of failures as the limit is exceeded.

If it does this, as it is believed to do, it is in all cases a safe guide, barring the risk of semi-fluid material existing beneath the foot of the pile; and in most cases a sufficient guide as well. But when a large number of piles are to be driven or extra heavy loads are to be sustained, ordinary prudence would dictate the ascertaining by experiment just what the piles will bear, or, if failure would do no great harm, taking chances with greater loads without experiment, under favorable conditions. The formula is not intended to be rigidly applied to such cases as this.

The valuable records below given, in comparison with the safe load by the Engineering News formula for safe load, may be abstracted as follows; and they seem to be fairly good proof that the Engineering News formula is, in fact, trustworthy to the extent above claimed for it.

Summary of Instances of Bearing Power of Piles given in more Detail below.

Case No.	Actual ultimate load.	Safe load by formula.	Factor of safety.	Material.
1	13,333	1,684	7.9	Mud.
2	14,560	6,067	2.4	"
3	22,400	23,450	—1.0	"
4	44,800	28,333	1.6	"
5	15,175 to 47,375	11,400	1.3 to 4.1	Alluv.
6	59,618	6,741	8.8	Mixed.
7	75,000	44,080	1.7	Sand.
8	224,000	112,000	2.0	....
9	13,440	8,020 to 9,520	1.7 / 1.4	Sandy. Mud.
10	6,400+ to 13,333+	10,183 to 20,000	Not determinable.	Sandy. Mud.
11	6,400– to 13,333+	10,667 to 11,790		" "
12	over 22,400+	37,500		"

Tests of Piles in which the Resistance to Extraction is the Only Evidence as to Ultimate Bearing Power.

Case No.	Actual ultimate load.	Safe load by formula.	Factor of safety.	Material.
13	490 to 1,288	108 to 251	.... /	Sandy. Clay.
14	15,850	25,067	....	Unknown
15	25,000 to 50,000	5,000 / 5,000	....	Rotten rock.
16	50,000 to 83,000	51,250 to 88,000	.... /	Sand. "
17	71,360 / 71,300	12,800 to 17,920	....	Clay. "

Caso 1.—Pile trestle at Aquia Creek, Va., 1871. Creek bottom, almost fluid mud over 80 ft. deep. Tide water 6 ft. deep. Trestle bents of six piles each, 12½ ft. between centers and about 15 ft. high. Piles 15 to 18 ins. diameter at butt, 50 to 56 ft. long, cut off just above low water-mark.

(The records show a 2,000-lb. hammer, falling 4 ft. with 8.5 ins. set or 9.7 ft. with 22 ins. set. Safe load by formula, 1,684 and 1,682 lbs. (but in reality the safe load in this case would have been computed under the data of Cases 10 and 11 below, which see). (Actual load 13,333 lbs. Continued actual safe load, 6,400 lbs.).

Case 2.—Philadelphia, 1873. (Soft river mud. Trial pile loaded with 14,560 lbs. five hours after driving, and sank but a very small fraction of an inch. Under 20,160 lbs. it sank ¾ in.; under 33,600 lbs., 5 ft.

(The records show 1,600 lb. hammer falling 36 ft. with 18 ins penetration. Safe load by formula 6,067 lbs.

Case 3.—Mississippi River at East St. Louis, 1868-69; soft muddy bottom, with 5 or 6 ft. of water. Piles in temporary railway trestle of three-pile bent, 15 ft. from center to center, driven about 20 ft. Penetration 2½ to 3 ins. The piles settled badly in a very short time under locomotives weighing not over 30 tons, so that the load on a pile could hardly have exceeded 22,400 lbs.

(Safe load by formula taking 27½ ft. mean fall, 2¾ ins. mean penetration, 1,600 lb. hammer; 23,450 lbs. Many of the data of this case are quite dubious, especially the weight given for locomotives. There were very few, if any, in Missouri in 1868-9 so light as 30 tons. It is more likely the load in each pile was double that stated.)

Case 4.—Perth Amboy, 1873; "pretty fair mud," 30 ft. deep. Four piles, 12, 14, 15 and 18 in. diameter at top, 6 to 8 ins. at foot, were driven in a square to depths of from 33 to 35 ft. Distance apart not given. A platform was built upon the heads of the piles and loaded with 179,200 lbs., say, 44,800 lbs. per pile. After a few days the load was removed. The 18-in. pile had not moved; the 12-in. pile had settled 3 ins., and the 14 and 15 in. piles had settled to a less extent.

(Hammer 1,700 lbs. falling 25 ft. with 2 in. penetration; whether the same for all the piles or not is not stated, indicating that the record is somewhat lacking in precision. Safe load by formula, 28,333 lbs.)

Case 5.—Fort Delaware, 1850. The account is highly unintelligible. Material, an alluvial deposit. The piles were of Chesapeake yellow pine weighing from 32 to 59 lbs per cu. ft. They measured 12 ins. square, and were about 30 ft. long, with points 5 ft long. Four trial piles were driven about 24 ft. (distance apart not stated) and capped with a platform upon which the loads were placed. The weight of ram is variously given at from 1,883 to 2,000 lbs. It appears to have been about 1,900 lbs.

(Safe loads by formula, calling fall 6 ft. and set 1 in. = 11,400 lbs., which checks quite accurately, as the piles settled 3-16 in. under 15,175 lbs. By gradual increments of loads extending up to 47,375 lbs., however, they only settled 1 in. in all, at the end of a period of 10 years. At the end of 5 years, with nearly 40,000 lbs. load, they had settled just ½ in.).

Case 6.—Proctorsville, La. Material, mud, sand and clay; wet. Trial pile (driven alone) said to have been 30 ft. long, yet it is said to have sunk 5 ft. 4 ins. by its own weight, and to have been driven 29 ft. 6 ins. deeper, making 34 ft. 10 ins. driven length. Cross-section, 12½ × 12 ins. at top, 11½ × 11 ins. sharpened to 4 ins. square at foot. Weight, 1,611 lbs. Head capped.

Pile bore 59,618 lbs. without settlement, but settled slowly under 62,500 lbs. Fall, during last ten blows, regulated to 5 ft. exactly. Penetration, last ten blows, ranged from ¼ to ½ in.; mean 0.35 in.; last blow, ⅜ in.

(Hammer 910 lbs. safe load, by formula, 6,741 lbs., being very far below what the pile actually sustained. This is another case of those piles in soft material whose resistance is not fairly measured by the blows given when first driving, but can only be fairly gaged by trying blows after the mud has had time to set.)

Case 7.—Buffalo. Material, wet sand and gravel. Piles driven in nests of from 9 to 13 piles. Test pile of beech., 20 ft. long after being driven and cut off. Driven length, 20 ft., 3 ft. in stiff clay; cross-section, 15 ins. diameter at top. A load of 50,000 lbs. remained on the pile for 27 hours, but produced no appreciable effect. The load was increased 20,000 lbs. at a time, and left for 24 hours after each increase. A gradual settlement aggregating ⅝ in. took place under 75,000 lbs., and the pile then came to rest. The total settlement increased to 1½ ins. under 100,000 lbs., and to 3 1-16 ins. under 150,000 lbs. During the experiments the ground was kept in a tremor by the action of three pile-drivers at work on the foundations. Subsequent use shows that 74,000 lbs. is a safe load.

(Hammer, 1,900 lbs.; fall 29 ft.; set, 1.5 ins. Safe load by formula, 44,080 lbs. As a "gradual settlement aggregating ⅝ in., took place under 75,000 lbs.," this 44,080 lbs. is as large a "safe load" as the circumstances warranted, unless some settlement was not objected to.)

Case 8.—Brooklyn, N. Y., 1847-48. Dry Dock at Navy Yard. Material, wet, loamy, micaceous, quartz sand, becoming quicksand wherever it was much trodden.

"The main piles were mainly round spruce bars, very straight, from 25 to 45 ft. long, averaging a driven length of 32 ft." "They were not less than 7 ins. in diameter at the smaller end, and 12 to 18 ins. (on an average, 14 ins.) in diameter at the larger end. The trial piles averaged 12 ins. in diameter in the middle. The heads of the piles were protected." The piles "were driven in rows 2½ ft. apart, and at transverse distances of 3 ft., all from center to center." But "intermediate piles, of very tough second growth oak, were frequently driven." "The piling machines were strongly and accurately made, with the ways bound with smooth plates of iron." They gave about one blow per minute. A Nasmyth hammer was used also, and gave 60 blows per minute. I have assumed that some of the piles tested were driven by it, although this is not stated in the reports. The author applies the test to a penetration of 0, but "the average distance driven by the last five blows was 1 in." We therefore take the experiments as embracing $s = 0$, and $s = 0.2$.

As the result of the tests it was believed that for a pile driven 33 ft. into the earth to the point of ultimate resistance with a ram weighing 2,240 lbs. and falling 30 ft. at the last blow, the extreme supporting power due to the frictional surface was 224,000 lbs., or 1 ton per superficial foot of the area of its circumference.

This case illustrates the criticism already made of Mr. Crowell's formula that, like Major Sanders', it gives excessive loads where the penetration is very small. For the ordinary machine, our formula here gives better results than Mr. Wellington's, but for the Nasmyth machine, which I have assumed to have been used on the piles tested, his results are almost exact, while ours are double the actual load.

(Safe load by formula, for 0.0 to 0.2 penetration, 134,000 to 112,000 lbs., or about half the estimated extreme supporting power. As there could hardly be a "better result" than this, the statement that the Trautwine formula gives "better results," is very incorrect in fact, and is based only on a comparison of ultimate loads, which for 0.2 penetration Trautwine has as 290,000, instead of 6 x 112,000 = 672,000 ultimate by the Engineering News formula.)

Case 9.—Dordrecht, Holland, 1872. Bridge over the Maas; temporary piles under staging. The author informs us that "the staging sank fully ¾ in., and during their erection the girders had constantly to be wedged up"; but leaves it to the ingenuity of the reader to deduce the other data required for our present purpose. The material seems to have been sand, with some mud; average depth of water, 19 ft.; maximum, 23 ft. The piles seem to have been driven either by a steam pile-driver delivering 60 blows per minute with a ram of 2,205 lbs., falling 30 ins., or by "an ordinary hand engine"; ram, 992 lbs.; fall, 6 ft. 7 ins. Both cases are given in the table. However this may be, we are told that "some of them went in much too easily, being driven ¾ in. and 1⅛ in. with the last blows." But "it was arranged, where the penetration was more than ⅜ in. on the average of the last 100 blows, to put in" additional piles. I therefore take ⅜ in. as the probable penetration. The load seems to have been about 13,440 lbs. per pile.

(Safe load for 2,205-lb. hammer, 8,020 lbs.; with 992-lb. hammer, 9,520 lbs. As the piles sank continuously but not hopelessly under 13,440 lbs., these loads check as well as could be desired.)

Case 10.—Aquia Creek. See Case 1. A pile 40 ft. long, after sinking some 30 ft. with its own weight and that of a 2,000-lb. hammer, was given a blow of 2-ft. fall, after which it sank 6½ ins. further in one minute under its own weight and that of the hammer, and then stopped. Four weeks later a 5-ft. blow failed to move it, and a blow of 14 ft. drove it only 4½ ins. This case and the following one illustrate strikingly the effect of time in increasing the stability of a driven pile. In both cases the blow recorded was delivered four weeks after the settlement under the load. A load applied after the blow, as usual, would undoubtedly have made a better showing for the formulas.

(Safe load by formula after 5 ft. blow with no penetration, 20,000 lbs.; after 14-ft. blow with 4½-in. penetration, 10,183 lbs.; actual load carried without failure, 6,000 to 13,000 lbs.)

Case 11.—See Case 1. A pile 43 ft. long received two blows of 2 ft. each, and then settled under 2,000-lb. hammer 1½ ins. in two minutes. Four weeks later it penetrated 2¾ ins. under a 10-ft. fall, and 8½ ins. under a 28-ft. fall.

(Safe load by formula, 10,667 and 11,790 lbs., respectively; closely corresponding with actual loads safely sustained.)

Case 12.—Lake Ponchartrain Trestle, La. About 6 miles of trestle crossed the lake proper, and the remainder (16 miles) crossed the adjoining sea-swamp. Four-pile bents, 15 ft. between centers. Material of swamp, several feet of soft, black vegetable mold, lying upon soft clay, with occasional strata 1 to 2 ft. thick, of sand. Piles sank from 5 to 8 ft. of their own weight, and then about as much more with hammer (about 2,500 lbs.) resting on head of pile. Two piles 65 ft. long were driven, one on top of the other, and penetrated 9 ins. with over 100 ft. driven; but a 30-ft. fall, 30 minutes after driving a pile, gave only 3 ins. penetration. Piles 65 to 75 ft. long. Weight of ram about 2,500 lbs. Fall, about 30 ft. Penetration, 3 to 12 ins. I have taken $s = 3, 6, 9$ and 12. "No settlement has been observed in the entire length of the structure to date." As there were four piles in a bent, and the bents were 15 ft. apart, the load on each pile probably has not exceeded 22,400 lbs. Although the extreme load is not given, we include this case as forming an interesting contrast with Case 3, also given by Mr. Bouscaren.

(Safe loads for 3, 6, 9 and 12 ins. penetration, 37,500, 21,430, 15,000, 11,538 lbs. As the only proper fall to be considered in a case like this is the 3-in. penetration, which occurred after 30 minutes' intermission, the check here is excellent.)

Case 13.—Small experimental piles. "Resistance of Piles to be Ice-drawn," by J. W. James. Material of various kinds, chiefly compact sandy clay, compact gravelly clay, with surface soil, sometimes wet, sometimes dry. The "piles" were small sticks of oak, as follow: Square, 1 to 2 ins. side; cylindrical, 1 to 2 ins. diameter; flat, 3¼ × 1 in. They had points of different shapes. A large number of experiments are recorded, of which the means given in the table are fairly representative.

Mr. Crowell's formula is hardly applicable to a case like this, for we have no way of finding his n, which is $\frac{1}{8}\sqrt{s'}$, where s′ is the penetration as it would be under a blow of a 2,000-lb. ram falling 20 ft. or other equivalent (?) blow of 40,000 foot-pounds. Since none of the loads reach 2,000 lbs., it is plain that the mere weight of a 2,000-lb. ram would have driven the pile indefinitely, and we can hardly doubt that any blow of 40,000 foot-pounds would have done the same, and would also have abruptly terminated the experiment.

(These curious records are of value only as checking the generality of a pile-driving formula, but in that way check extremely well, as follows:

Wt. ram, lbs........	22.8	24.9	23.8	32.2	23.1	39 0
Ht. fall, ft...........	4.6	7.6	7 2	7.2	7.3	6.8
Set., ins..............	.94	.89	.36	.45	67	.76
Safe ld. by formula.	108	200	251	231	203	301
Observed resistance.	490	572	1,288	822	712	959
Ratio, 1 to...........	4.5	2 9	5.1	3.5	3.6	3.2

When it is remembered that the "observed resistance" is merely that to pulling, the formula for safe load could hardly check better with the actual observations.)

Case 14.—Ice-drawn pile. Observations made January, February, March, 1873. From the paper quoted in case 13. Material not stated. Pile about 12 ins. diameter, under a bridge constructed during the previous year across a river confined by a mill-dam. The fall was approximately 20 ft. "The driver (940-lb. hammer) was worked on the ice, and equal lengths of the piles did not project above its surface when the last blow was delivered." The penetration is said to have been ½ in. The load was estimated by the uplifting force of ice. "The piles held their ground, and the ice broke away, until it had attained a thickness of 15 to 16 ins., when the piles began to come up." The lifting force was estimated, from experiments by the author upon small, smooth sticks, at 18,850 lbs. per pile. Deducting weight of superstructure, about 3,000 lbs., leaves 15,850 lbs. as the estimated force required to draw the pile.

In view of the smallness of the actual load in this case, it may reasonably be asked whether much of the energy of the blows was not consumed in overcoming the friction of the piles against the ice through which they were driven. It will also be noticed that the force was an up-lifting one, and that its amount was estimated by means of the adhesion of ice, as derived from experiments with small, smooth sticks. The weight of ram, height of fall and penetration, were all taken by the author of the paper at hearsay, from a man who had worked on the bridge. The case is, in fact, one of exceptional doubtfulness in all respects.

(Safe load by formula, 25,067 lbs.; agreeing sufficiently well with probabilities.)

Case 15.—Proposed Cambria Reservoir, Philadelphia, 1883. Notes by the writer. Material, wet, decomposed mica schist. A wrought iron pipe, 3½ ins. outside diameter, 3 ins. inside, was inserted in a bore-hole 6 ins. in diameter and 30 ft. deep, and driven 14 ft. to rock. The lower end of the pipe was dressed to an annular cutting edge. Load.—After several hours' work with block-and-fall, the pipe was pulled in two by using two hydraulic jacks of unequal power, one on each side, by means of which the pipe had been raised 8 ins. The fracture took place in the thread, where the wall thickness was reduced from ¼ to ⅛ in., leaving a cross-sectional wall area of 3⅛ × 3.1416 × ⅛ = 1.23 sq. ins. Since the pipe had risen slightly under the pull which soon after caused its rupture, the latter was evidently about equal to the resistance of the pipe to being withdrawn. We can estimate at the amount of this pull by estimating the tensile strength of the iron at the point of rupture. The conditions of the experiment were very crude, but considering that the pipe was no doubt weakened by canting from side to side under the unequal forces exerted by the two jacks, as well as by repeated blows in driving, and repeated tensile strains in drawing, and by the removal of the outer "shell" of the iron in cutting the thread, the tensile strength could hardly have exceeded 40,000 lbs. per sq. in., and, on the other hand, it was perhaps not less than 20,000, giving 25,000 to 50,000 lbs. as the extreme load.

(Hammer of 350 lbs. falling 8 ft., set ⅛ in., sustained 25,000 to 50,000 lbs. Safe load by formula, 5,000 lbs. scant.)

Case 16.—Pensacola, Fla. Material, clean, hard, sharp, white quartz sand. All the sand would pass through a sieve having openings 1-12 in. square. Water filtered through it came out perfectly clear. One cu. ft. of it would hold 6 qts. of water. The 2-ton hammers could only drive about 20 ft. The water was about 11½ ft. deep. Seven piles, selected as representing the average of all, were tested with upward pulls of 20,000 lbs. each without moving, and one of these was afterward tested with upward pulls sufficient to cause motion (as recorded below) and finally withdrawn. This pile was 20 ft. long, 16 ft. in sand, including its point, 2 ft. long. One foot of this length was in loose sand, which had been excavated and had fallen back. The average diameter of the part in the sand was 13¼ ins., including the bark. Weight of pile, 1,632 lbs. Pile tested two months after it was driven. Neither weight nor fall of hammer nor set given.

The following guesses at their values are the result of laborious study of their remarks respecting the foundation piles as a whole, and are to be taken as of very doubtful correctness:

				(Safe load, by formula.)
1st.	$w = 2{,}200$,	$h = 30$,	$s - 0.5$.	(88,000)
2d.	$w = 4{,}100$,	$h = 33$,	$s = 0.0$.	(270,000)
3d.	$w = 4{,}100$,	$h = 10$.	$s = 0.6$.	(51,250)

The tests on the trial pile resulted as follows:

78,000 lbs....No movement,
80,000 " ...Resisted ½ min.., and then rose very slowly. Rose 2½ ins. in 30 min.
82,000 " ...1⅜ min.,
83,000 " ...½ min. Rose 2¼ ins. in all, in 30 min.
60,000 " ...18 hours. No movement.
64,000 " .. } Rose 3 ins. in one hour, 6 ins. in all.
74,000 " .. }
50,000 " ...For two days. No movement.

The very small loads obtained by the test in this case seem to confirm the view already expressed that the resistance of a pile to an upward pull must be less than that to a downward pressure. This is especially noticeable in comparison with the Brooklyn tests, Case 8, where the conditions were nearly similar, but where the pile (tested by pressure) bore much greater loads. The sand at Pensacola was remarkably pure, and hence could probably exert little resistance to being broken up, while offering great resistance in the opposite direction, as is shown by Mr. Towle's statement that at a depth of 15 ft. a 2-ton ram (falling 33 ft.) rebounded nearly a foot.

(The safe loads by formula, as interpolated above, check very accurately with the probabilities indicated by the test.)

Case 17.—Albert Dock, Hull, England. Removal in January and February, 1880, of coffer-dam built in 1874. Material, compact bluish clay, above which there were from 3 to 5 ft. of peat, and above this silt and sand in places. Piles of ordinary rough Memel bark timber, from 10 x 12 to 14 x 15 ins. Average, 12½ ins. square. From 20 to 40 ft. long. Driven length, from 6 to 30 ft.; average, 18¼ ft. Most of the piles were driven from 10 to 20 ft. into the clay and were nearly or quite in that material alone; but a few of the shorter piles, driven in a sloping side of the dock, were entirely in the silt, while a few others entered the peat without reaching the clay. The piles were driven close together in two rows 5 ft. apart, forming a coffer-dam, the space between the two rows having been filled with puddled clay "to above high water mark." Before the piles were withdrawn the puddle was removed down to a level "rather under high water-mark of ordinary neap tides."

The height of fall (2,240-lb. ram) varied from 5 to 6 ft., and the penetration from 0.5 to 0.75 in. I have taken the extreme cases; 420 piles were withdrawn and 300 observations recorded. The force was applied by men working a winch and estimated by testing that of the men in lifting known weights. The piles were drawn consecutively, so that one side of each pile was nearly or quite free from frictional contact, the opposite one was in loose contact with the adjoining pile, and only the remaining two sides resisted by friction with the ground.

The average total force required to draw a pile was 75,869 lbs. The author deducts from this 2,340 lbs. (= 12 × 12 ins. × 15 lbs. per sq. in.) for suction, and 2,240 lbs. for weight of pile, leaving, say, 71,300 lbs. as the frictional resistance to drawing the pile.

(Safe load by formula, with ¾-in. set after 5 ft. fall, 12,800 lbs.; with ½-in. set after 6 ft. fall, 17,920 lbs.)

(From Engineering News of March 9, 1893.)

Sir: Your article on "The Actual Resistance of Bearing Piles," in the News of 23d inst., conveys so erroneous a conception of our formula that I find myself reluctantly compelled to appear again in print upon this subject.

The most serious matter in your presentation of our formula in the article referred to is the implication that the formula leaves the engineer, in any given case, with no more definite instructions than that the safe load is to be taken at from one-half to one-twelfth of the extreme load, as given by our formula.

Our factor of safety does, indeed, range from one-half to one-twelfth, as stated briefly in several places in my discussion of Mr. Crowell's paper, but that the implication referred to is utterly misleading will appear at once from the fact that our rule (Pocket Book, page 644) reads:

As to the proper load for safety, we think that not more than one-half the extreme load given by our rule should be taken for piles thoroughly driven in firm soils; nor more than one-sixth when in river mud or marsh. If liable to tremors, take only half these loads.

Now, in any given case the engineer knows whether the bottom is of "firm soil" or of river mud or marsh," and whether the structure is such that the piles will or will not be "liable to tremors." Hence our rule gives a set of maximum factors of safety as follows:

	If not liable to tremors.	If liable to tremors.
Firm soils................	one-half	one-fourth
River mud or marsh......	one-sixth	one-twelfth

from which one factor is to be selected for any given case, and in accordance with the peculiarities of that case.

In the face of this to intimate, as you now do, that our rule says simply "for safety take anywhere from one-half to one-twelfth of the extreme load given by the formula " is as grotesque a misrepresentation as it would be to take a case where the fall h is stated as "somewhere between 5 and 30 ft.," and argue that your formula was of no use because it gave loads varying from L to 6L; while to make it appear, as does your table on page 171, that our formula, FOR A GIVEN CHARACTER OF SOIL, gives results varying from one-half to one-twelfth of the extreme load is as unjust as it would be to take a case with a fall of 10 ft., and claim that your formula gives for that case results varying from L to 10L because it is intended for heights of fall of, say, from 3 to 30 ft.

I therefore beg to submit, as below, a version of this table, in which the safe loads given by our formula are stated as the wording of our rule requires, taking occasion, at the same time, to rectify a scarcely less glaring oversight on your part in classing extreme loads and safe loads without distinction under the common head of "actual loads," as well as to correct a few small errors in your calculation, and one or two greater ones in your statement of the data.

Treated justly, as above, our formula will be seen to compare favorably (as far as these few records can show) with one which is claimed to be "in all cases a safe guide."

Noting your remark that the foregoing seven cases, "which are given in Trautwine's 'Pocket Book,' are in addition to the following list" of 17 cases taken from my discussion of Mr. Crowell's paper, I may remark, as stated on page 147 of the discussion, that the latter were restricted chiefly to those results "which give, or from which we may infer, the ultimate or extreme load," that hence the first four and the last one of the seven results which you now quote, giving, as they do, only the safe load, were necessarily omitted from the list given in the discussion, while the fifth and sixth, which give the extreme load, are included in that list, forming cases 2 and 6 (Philadelphia and Pensacola), respectively.

	Soil.	Weight of ram, pounds. *w.*	Height of fall, feet. *h.*	Penetration, inches. *s.*	Actual load, pounds.		Loads by formulas, pounds.					
							Engineering News.	Trautwine.				
					Extreme.	Safe.	Safe load $=\frac{2\,w\,h}{s+1}$	Extreme $=\frac{50\,w+\sqrt[3]{h}}{s+1}$	Maximum factor of safety.		Maximum safe load.	
									Steady	Tremors.	Steady	Tremors.
Chestnut St. Brid'e, Phila.....	River mud	1,200	20	0.75	......	40,300	27,430	93,100	⅙	1/12	15,500	7,750
Neuilly Bridge...	Gravel	2,000	5	0.016	......	105,300	19,685	168,300	½	¼	84,150	42,075
Hull Docks	Mud.......	1,500	24	2.00	...	45,000 to 56,000	24,000	72,100	⅙	1/12	12,000	6,000
Royal Bord'r Bridge	Sand and gravel...	1,700	16	0.05	......	156,800	51,800	204,000	½	¼	102,000	51,000
Philadelphia, 1873	Soft river mud.....	1,600	36	18.00	14,560 to 20,[illegible]60	.....	6,060	13,930	⅙	1/12	2,3[illegible]0	1,160
Pensacola (U.S. trial pile)......	Silt, sand and clay	910	5	0.375	59,600	....	6,6[illegible]0	56.600	⅙	¼	2[illegible],300	14,150
French rule	Not stated	1,344	4	0.013	....	56,000	10,610	105,200	Given data insufficient.			

There is another point in your article to which I must refer, and that is your summing up of the results of the comparison, in my discussion, between the actual results collated and the loads obtained from the three formulas. I give these results below, and repeat, as stated on page 153 of my discussion, that "the first eight may be considered good cases; the conditions of driving and loading correspond with what may be called ordinary practice, and in most of these cases are stated with reasonable clearness." The other nine cases are much less reliable. (We give only the first eight to save space and time.—Ed.):

In this comparison:

R = the actual extreme load on one pile.

R_w = the extreme load on one pile by the Engineering News formula.

R_t = the extreme load on one pile by the Trautwine formula; and, inasmuch as the quotients given are the ratio of the loads by the formulas to the actual loads, the approximation of the formulas as to these results is closest when the quotient approaches most nearly to unity.

A.—Piles tested by loading.

Case No.	$\frac{R}{R_w}$	$\frac{R}{R}$
1	1.320	0.798
	1.321	1.439
2	0.400	1.047
	0.554	1.450
	0.924	2.415
3	0.187	0.383
	0.136	0.315
4	0.263	0.541
5	0.693	0.549
6	1.545	1.084
7	0.284	0.643
	0.378	0.857
	0.567	1.285
8	0.278	0.644
	0.333	0.772
	0.926	0.462
	1.111	0.555
Mean	0.660	0.896
Maximum	1.545	2.415
Minimum	0.136	0.315

As I have already stated, I do not consider the evidence of these cases sufficient either to establish or to condemn any formula; but they are all that I could find, and, taking them for what they are worth, and bearing in mind the greater reliability of the first eight cases, I had flattered myself (though modesty, of course, constrained me to leave it for you and for others to note and proclaim the fact) that the result of this comparison was distinctly favorable to our formula, and I am naturally surprised, therefore, to learn from you that it "clearly shows that the Engineering News formula gives the closest approximation of the three." John C. Trautwine, Jr.

(The reason why we took an unfavorable view of the comparative results of the Trautwine formula can be very briefly, and we think conclusively, shown from the eight instances referred to, by comparing the SAFE loads which the two formulas give, using Mr. Trautwine's own factors, as follows:

			Mean ratio of formula safe load to bearing power by test.	
Instance.	By Trautwine formula. Conditions.	Factor.	Trautwine.	Eng. News.
1	Mud, tremors.	1-12	.095	.22
2	Mud, tremors.	1-12	.14	.10
3	Mud, tremors.	1-12	.03	.025
4	Mud, no tremors.	1-6	.09	.04
5	Mud, no tremors.	1-6	.045	.12
6	Mud (?), no tremors.	1-6	.09	.26
7	Sand, tremors.	1-4	.23	.07
8	Sand, no tremors.	1-2	.30	.11
Mean			.121	.118

The face of these returns looks as if the two formulas were much of a muchness, but let us look further. The three instances in which it looks as if the safe load by the Engineering News formula was decidedly too low are Nos. 4, 7 and 8, yet in all three of these instances the full data, as abstracted in our issue of Feb. 23, show that, as a matter of fact, the Engineering News formula gives as great a safe load as is warranted. In case No. 4 piles settled under 44,800 lbs. and the formula gives 28,333 lbs. safe load. In case No. 7 piles settled under 75,000 lbs. and the formula safe load is 44,080 lbs. In case No. 8, the formula gives just half the estimated extreme supporting power. Therefore, in these three instances, the Trautwine formula appears to give a greater load than is really safe.

We may or may not have been right in thus reasoning from these particular records, but as Mr. Trautwine himself admits that his formula is not consistent under extreme cases of fall, giving far too high values for low falls and vice versa, owing to its making the bearing power vary with the cube root of the fall, we fail to see why he should so strenuously insist that the formula chances to fit certain particular instances as well or better than others, even if it did so. Supposing this absolutely proven; what then? It is known that in certain other cases it would not be so trustworthy. The Trautwine formula would naturally fit the seven instances quoted from the Pocket-Book pretty well, since it was framed to fit those instances only or chiefly. It is not probable that Mr. Trautwine framed it to fit any other specific records, or he would have quoted them.

As for the Trautwine factors of safety, it seems to us absurd to maintain that the intent of the sentence quoted is to give four specific factors to be used in four specific instances. The factor it specifies in effect is "from 1-2 to 1-6, but only half as much if liable to tremors." What structure was ever built that was not "liable to tremors," if only from earthquakes? Practically, the specification is for a factor of 1-2 to 1-12, according to the engineer's judgment.

For again, if the sentence as to factors be taken literally, as suggested, it inculcates exactly the reverse of good practice. To conform with the uniform results of experience, as indicated in recent discussions, it should rather read as follows:

"For piles driven in firm soils about 1-6 of the extreme load by formula may be taken; but when driven in river mud or marsh, one-half, or even the full formula load, or even two or three times that load, may be taken with about the same assurance of safety as 1-6 in firm soils."

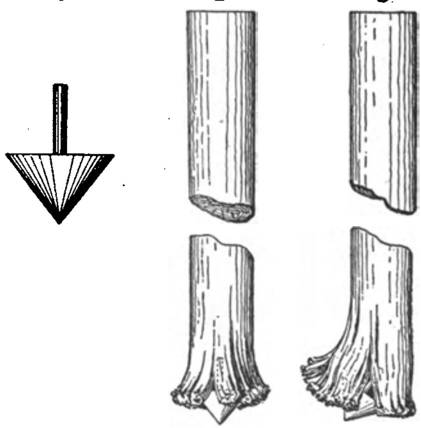
The error in the original sentence lies in the fact that it allows twice over for the weakening effect of mud and soft material on the supporting power. No one doubts that a pile driven in mud is absolutely of far less value than one driven in firm soil; but that effect is far more than included in the comparative bearing power by any and all formulas which are based on the mean penetration under the last blows; because all experience indicates that the final bearing power of piles driven in mud is abnormally great in relation to the rate of penetration when driving, and not abnormally small. The supposed and sufficient explanation of this fact is that soft mud gradually settles into every fiber of the pile, so as to get a very firm grip upon it; whereas no such effect takes place with firm soils.

This fact alone shows that the sentence in question was not a carefully studied provision of four different factors for four different conditions, but rather that the thought in the mind of the writer was essentially as we interpreted it.—Ed.)

EFFECT OF USING CAST IRON SHOES.

Sir: Noting your article and comments on pile driving in issue of Dec. 8, the following experience may be of interest to those of your readers who may be called upon to drive piles through cribwork and old timbers, such as I had occasion to do recently for the Department of Docks, at the foot of Canal St., North River, New York. The nature of the cribwork was unknown, and the quickest and best method of driving was determined by a series of tests as the work progressed. At first the piles were shod with cast iron shoes, as shown in Fig. 1, but failed, as shown in Figs. 2 and 3.

1 2 3



Effects of Driving Piles Having Cast-Iron Shoes.

The piles were next driven with the point cut off square, but broomed points and split and broomed heads appeared to such an extent that the method of pointing was resorted to with very favorable results.

The piles used were sound and straight spruce and yellow pine sticks, the latter giving much better results, and withstanding the 60 to 70 blows of a 3,000-lb. hammer, falling 10 ft., much better than the spruce.

Eugene Lentilhon,

New York, N. Y., Dec. 14, 1892. J. Am. Soc. C. E.

EFFECTS OF OVER-DRIVING OF PILES.

(From Engineering News of Dec. 8, 1892.)

By Robert L. Harris, M. Am. Soc. C. E.

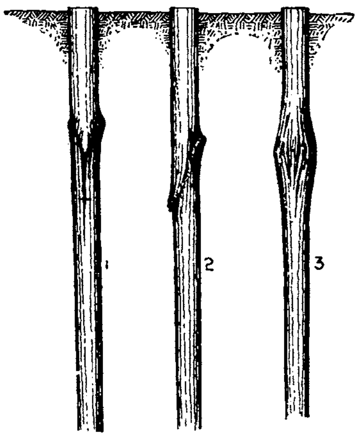
Many years ago engineers used to be instructed and required to drive piles to a very small movement at the last blow, even so low at times as ¼ in. Common sense rebelled at this, and so soon as the writer came in responsible charge of work, he seldom permitted it. In 1879, an ocular demonstration not only showed the correctness of this long held position, but caused a loss of faith in piles driven to small movements for many cases.

The projected line of the Boston & Hoosac Tunnel & Western Ry. passed under the Troy & Greenfield (then in operation), in two places, both of which were at embankments of sand. After some years of litigation the first named road was permitted to be completed; naturally it derived no assistance from its opponent. For the proposed openings, to be spanned by iron bridges on masonry abutments, temporary bents of piles were driven in the embankments to about 22 ft. below track level of the T. & G. R. R., to allow excavation for the abutments, etc., at the under crossing. The fine compact sand caused hard and slow driving. In the subsequent excavation which soon followed it was found that over one-half of these piles were next to worthless, being split or broken from the driving at depths below 8 ft. in one or more of the three ways indicated by accompanying sketches; and in these cases the bents had to be "posted down."

Most of the piles failed as shown in Fig. 1; some of them, however, as in Fig. 2, and a few only as in Fig. 3.

In the code of rules (p. 1) there is mention of the bad effect of "broomed heads," but broomed points are hardly touched upon, which naturally brings up a second practical point early learned, about which many engineers and contractors will differ with the writer until they may make fair trial.

In most kinds of materials a pile will drive better, truer and nearly as rapidly, if merely cut off square at the lower end than if pointed; and, strangely enough, this proved so even in indurated sand where marking stakes required pointing or



Modes of Failure of Over-Driven Piles.

holes made for them. Although cutting off piles saves labor of handling and pointing, yet only a demonstration convinces engineers and contractors of the benefit; once tried, however, neither will thereafter point, except under "cast iron specifications."

(The point that piles will, as a rule, drive better without sharpening than with, is now, we believe, generally accepted practice. An iron shoe, if used, is also of very little assistance, generally stripping off before it has penetrated far.—Ed.)

ON THE NASMYTH STEAM HAMMER.*

By Don J. Whittemore.

Having used the Nasmyth steam hammer in driving piles in foundations for masonry at the La Crosse and Sabula bridges and for elevator foundations in Milwaukee, it may be proper for me to testify that in my opinion no engineering plant is complete that does not include this appliance, and I fully indorse all that was written in its favor over thirty years ago by Wm. J. McAlpine, Past-President of this Society.

I wish to present some evidence of how far the effectiveness of this machine is dependent on keeping a firm head to the pile. Whenever the head of the pile becomes broomed from repeated blows of the hammer, though this brooming may not extend to a greater depth than from one-half to one inch,

The	3d	foot	of penetration	required	5	blows.
"	4th	"	"	"	15	"
"	5th	"	"	"	20	"
"	6th	"	"	"	29	"
"	7th	"	"	"	35	"
"	8th	"	"	"	46	"
"	9th	"	"	"	61	"
"	10th	"	"	"	73	"
"	11th	"	"	"	109	"
"	12th	"	"	"	153	"
"	13th	"	"	"	257	"
"	14th	"	"	"	684	"
			Head adzed off.			
The	15th	foot	of penetration	required	275	blows.
"	16th	"	"	"	572	"
"	17th	"	"	"	832	"
"	18th	"	"	"	825	"
			Head sawed off.			
The	19th	foot	of penetration	required	213	blows.
"	20th	"	"	"	275	"
"	21st	"	"	"	371	"
"	22d	"	"	"	378	"
		Total number of blows..........			5,228	

* Republished from Transactions Am. Soc. C. E., Vol. XII., p. 441, 1883.

the useful effect of the blow is partly lost through extreme elasticity at the pile head. The following data as to the driving of a green Norway pine pile at Sabula illustrates how far this obtains. The pile was brought to its position between the leaders and dropped through 10 ft. of water and penetrated the silt of the river bottom to a depth of 2 ft., and then the hammer commenced its work:

A pile of about the same size as the one mentioned above, driven near the same locality and to the same depth, but with no adzing or sawing off the head during driving, required 9,923 blows. The ram weighed 2,800 lbs. and dropped 36 ins., 65 times per minute.

At Sabula, about 2% of the 700 piles driven by this appliance ruptured slightly just below the ring support at the head of pile, and the friction produced by the wood fibers working on each other under the repeated blows of the ram was sufficient to ignite and burn the heart of the head of the pile quite across, as will be seen by an examination of the specimen now exhibited.

I add one other remark. This machine is being manufactured and is called by the manufacturer after an individual who has added several perhaps very important minor details that have made it a little more practicable than it was thirty years ago. But wherever the members of the American Society of Civil Engineers witness the operations of this machine. I desire that they shall not drop the name of the Scotchman who was its inventor—James Nasmyth.

SOME FACTS OF EXPERIENCE IN PILE-DRIVING.

(From Engineering News of Dec. 8, 1892.)

By Mr. W. B. W. Howe.

Several years ago, being called upon to design and construct certain railroad terminals, a large portion of which was to be located upon a soft marsh averaging probably 70 ft. in depth, it became necessary to determine with a reasonable degree of accuracy the supporting capacity of piles driven into, but not through the stratum. This was particularly necessary as much of the work was to be of a temporary character where it was inadvisable to incur the expense of securing piles long enough to penetrate to the solid bottom.

The following test was made:

A pile driver was selected and the guides graduated so that the fall of the ram could be readily noted for each blow, as well as the penetration of the pile and its depth in the ground. A pile of known length, 12 ins. square, (weight 1,500 lbs.), was secured. The ram weighed 1,950 lbs. and was tripped automatically at the zero point on the guides. The result of the first pile test is tabulated below:

No. blow.	0.	0.	1.	2.	3.	4.	5.	6.	7.
Fall, ft.	0.	0.	10.5	13.	15.	16.5	19.	20.5	22.5
Set, ft.	5.0	6.5	2.5	2.0	1.5	2.5	1.5	2.0	1.5
Depth in ft.	5.0	11.5	14.0	16.0	17.5	20.0	21.5	23.5	25.0
Contact surface sq. ft.	20	46	46	56	64	70	80	86	94
Coefficient of resistance lbs. per sq. ft.			445	453	457	460	463	465	472

(The last line is obtained by dividing the total energy of the blow in foot-pounds (fall in ft. × wt. hammer in lbs.) by the area of surface of the pile in contact with the earth. We have checked through the computations, and find them correct, but the large and round figures for the set have a somewhat suspicious look.—Ed.)

It is curious to note how uniform the coefficients in the last line above are, and it may be a fair conjecture, whether the gradual increase from 445 lbs. per sq. ft. under a fall of 10.5 ft. to 472 lbs. per sq. ft. under a fall of 22.5 ft. may not be due rather to the loss of energy as the fall increases than to an actual increase in the coefficient itself. These seem to me too great to be attributed to the friction of the mud upon the sides of the pile, when the short interval between the successive blows of the ram is taken into consideration. It is of course impossible to determine, without experiments specially directed to that end, how much may be due to the resistance at the point of the pile. The data therefore have no special bearing upon the present discussion and are only given for what interest they may possess. Similar records were made of over 100 piles, and more or less complete observations upon more than 1,000 piles driven in the same locality serve to confirm the general character of the special tests made.

In order to ascertain what increase in stability the piles would probably acquire over that indicated by the excessive settlement at each blow of the ram, several tests were made by carefully noting the penetration at the last blow, and suspending operations for twenty-four hours, at the expiration of which, driving was resumed. In almost every instance the penetration at the first blow was but one-fifth of what it had been under the last blow on the previous day, gradually increasing after two or three blows, until the full penetration was reached, showing very clearly that a longer interval, than that between the successive blows of the ram, was required to enable the mud to attain its full grip upon the pile.

One case possesses sufficient interest to be recorded. The pile in question was driven in a temporary trestle, penetrating 40 ft. into the mud and settling 26 ins. under the last blow of the ram, falling about 20 ft.

The ultimate (not safe) sustaining capacity of this pile as determined by the several formulas given by Mr. Crowell would be as follows:

Sanders	18 460 lbs.
Engineering News	18 080 "
Crowell (a)	18,210 "
Trautwine	10,037 "

And yet the location of this pile was such as to load it many times each day with about 18,000 lbs., and after the expiration of two years no settlement could be detected. It is evident that in this particular case the formulas all give too small ultimate loads, because, the conditions upon which they are based are not those which control the actual supporting capacity of the pile.

Contrast the foregoing example with another case. A similar work was undertaken in a different locality, but the character of the strata through which the piles were driven differed in every respect. The marsh was underlaid at varying depths by a hard bed of sand. The overlying mud being so soft that one or two blows of the ram would drive the pile down to the sand, in some instances more than 30 ft. Tests indicated that after the expiration of 24 hours of rest, the conditions remained unchanged. The first blow of the ram caused the same penetration as did the last blow on the previous day. It was evident, therefore, that the supporting capacity of the piles must be derived from the sand stratum underlying the mud, and into this they were driven, settling at the last blow of a 2,240-lb. ram falling 25 ft., from 1½ to 3 ins. The underlying stratum of sand varied in depth, and in several instances single sections of piles were not of sufficient length. It was, therefore, necessary to drive one or more additional sections upon the first, the connection being made with ordinary dowel pins. Estimating the bearing capacities of these piles by formula, the following comparison (taking s=2 ins.) may be had:

	Gross.	Safe.
Sanders	336,000	42,000
Engineering News	224,000	37,333
Crowell (a)	292,180	48,697
Trautwine	109,013	54,506 to 9,085

The conditions of loading to which these piles were subjected, were in every way similar to those mentioned in the previous case; and yet, all of the single piles settled appreciably, while those composed of two or more sections, end to end, yielded but slightly or not at all.

I do not know of two instances that more forcibly illustrate the effect of the material penetrated. In the first instance, the ultimate sustaining capacity of the pile, by formula, is but 18,080 lbs. while in actual and almost hourly service this load was reached without causing further settlement for two years at least. While in the second instance, although the indicated ultimate resistance by forula is over 200,000 lbs., and the safe load, by the most conservative (Engineering News) formula, 37,333 lbs., the piles have failed at less than one-half that amount. It is worthy of special note, and I shall refer to the fact later, that in the second example the single section piles showed appreciable settlement while those composed of one or more sections did not.

In contrasting the two cases the reasons for the differences are not far to seek. In the first case the marsh mud was of a peculiarly tenacious character, tough and sluggish in its movements. Having being displaced by the pile in driving it required a considerable time to restore itself to grip the stick, but once having done so, it possesses sufficient elasticity to admit of considerable lateral displacement without breaking away. But in the second case the point of the pile was in sand, a material not composed of these properties, and although the piles were fairly well driven as regards the settlement at the last blow, the continued vibration set up by passing trains being transmitted to the point, gradually worked them down. This vibration, although affecting in like manner those piles composed of two or more sections, was dissipated in the upper sections and failing to reach the point, could not produce that disturbance of the sand necessary for settlement to take place. I believe this to be the explanation of the stability of these double section piles.

The tendency of piles driven in sand to work themselves down if exposed to vibratory motion, is well known, and seems to be entirely independent of the settlement at the last blow of the ram. In my own experience, I have known very many to settle under a load of about 18,000 lbs., although driven to ½-in. settlement with a 1,200-lb. ram falling 20 ft.; principally, I believe, because the limit of penetration, ½ in., would be reached before the pile had been driven deep enough to prevent its rocking, so to speak, on its point. I cannot now call to mind a single instance of piles driven into the sand and exposed to vibrations that have not settled more or less unless driven quite deep. It is my practice and has been for some years to require all piles to attain a certain minimum depth, regardless of how small the penetration at the last blow may be, unless some firm and reliable stratum can be reached.

In conclusion, if it can be established, as I think, that the individual peculiarities and properties of the soil penetrated must appear as a factor in any expression for the bearing capacity of a pile, and that factor cannot be measured by "s," I do not see how it is possible to use any formula without expending as much labor in determining the particular constants and coefficients necessary, as would be involved in making an actual test upon the ground by piles driven and loaded. Many other instances might be given which would seem to indicate a like conclusion, but I have already occupied more of your space than I had intended.

(Comments by Editor of Engineering News.)

What would our correspondent propose to do, simply guess at the bearing power of piles? This seems to be the legitimate inference from the opinions he expresses, but the facts which he advances in support of those opinions seem to us quite consistent with the opposite view; viz., that a proper formula properly used will at least let a man know when he is or is not within the limits of safe practice. Taking up his examples seriatim the first one is not accompanied by any evidence of bearing power. By the Engineering News formula their safe bearing power would be

$$\frac{2 \times 1,950 \times 22.5}{18 + 1} = 4,650 \text{ lbs.}$$

if measured by the penetration without intermission after blows. If in this case, as in the one next given, the penetration after 24 hours was only one-fifth as great, the safe load would be increased to about 19,050 lbs., the ultimate being in each case six times as much.

In the next case, the safe load was found to be 18,000 lbs., whereas the several formulas (excluding that of Trautwine, which was erratic) showed an ultimate of only 18,080, the safe load by formula being only 3,013 lbs. But if, as stated, the penetration was only one-fifth as great after 24 hours' rest, the safe load by formula becomes about 15,000 lbs., and the ultimate 90,000. Does not the actual 18,000 lbs. check pretty well with this?

The third case presents the very extraordinary result that in piling across a deep and soft marsn those piles which were spliced out to 60 to 90 ft. afterwards stood a load approaching nearly to the formula safe load, while those piles which were

ALLEGED to have touched hard bottom without splicing did not stand half the formula safe load! Has it occurred to our correspondent that perhaps his contractor or foreman was trifling with his confidence, and represented the actual status of those unspliced piles differently from what it was? It is against nature that the sand bottom to a deep marsh should be so very irregular as the statement of alleged facts implies; and no formula can possibly be made general enough to cover and provide for the 'possum element in the soul of a contractor. Nothing but eagle eyes can do that, and they not always.

Finally, our correspondent says that he has known short piles driven to ½ in. set by a 1,200-lb. hammer falling 20 ft. to settle under 18,000 lbs. The safe load for such a pile by the Engineering News formula would be

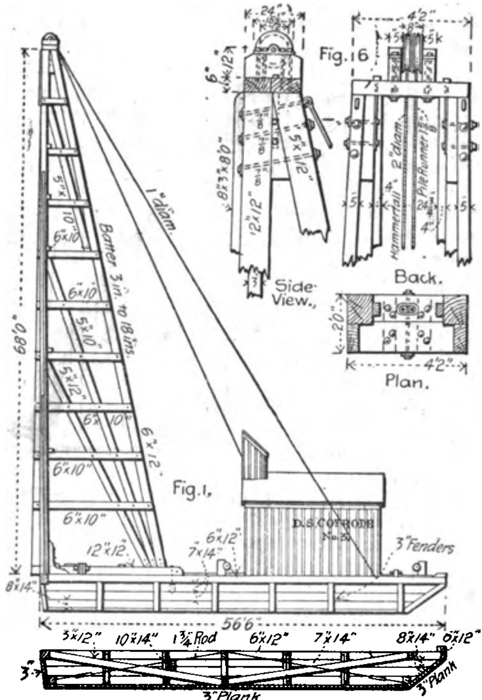
$$\frac{12{,}000 \times 20 \times 2}{0.5 + 1} = 32{,}000 \text{ lbs.}$$

and while agreeing with our correspondent that no pile which has not penetrated a reasonable distance into the earth can be regarded as safely driven, we "don't the fact," like the Scotchman, that any pile ever rationally driven into sand not underlaid by mud, and under the other conditions stated, has ever failed under a fairly imposed load of 18,000 lbs. Were there not some unstated modifying circumstances or elements of doubt in this case?

PILE-DRIVING MACHINE.

The machine illustrated is one of the very latest in model and the heaviest in New York harbor.

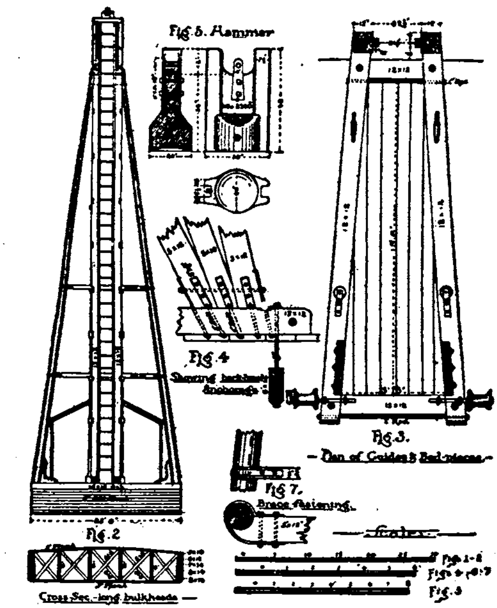
The hull is 56 ft. 6 ins. long and 23 ft. 6 ins.



Longitudinal Section Showing Internal Bracing.

wide, over all; each of the sides of the hull is made of four pieces of yellow pine, the two lower each 8 × 14 ins., the third 7 × 14 ins., the top piece

6 × 14 ins., all securely tied by through bolts; the bow planking is oak, 5 ins. thick; the bottom and end plank yellow pine, 3 ins. thick. The bow is further strengthened by a 16 × 16 in. cross-timber at top, and at the stern is an 8 × 12 in. cross-timber of yellow pine. Oak is used on the bow as being



better adapted to stand the constant wear of the piles hauled against it; and to prevent knots or inequalities on the piles interfering with their position under the hammer, the bow planking overhangs 6 ins. in its total height.

The chief end in the design of a hull for a floating pile driver is to obtain longitudinal stiffness, so that the strain between the bow and engine may be properly distributed. To this end our hull is strengthened lengthwise by four wooden bulkheads or keelsons, each 6 ins. thick (Fig. 2) and braced laterally by the four sets of X braces of 6×6 timber. The hull is further braced in the center by two 3×12 in. yellow pine braces and tie rods or "hog chains" of iron 1¾ in. in diameter. Wale-pieces and fender plank 3 ins. thick protect the outside of the hull against chafing; the deck has a "crown" of about 6 ins. in its total width.

The hammer-guides are made of two pieces of 12×12 yellow pine, 67 ft. long from out to out, with inside of guides 5×4 in. stuff protected by plate iron ¼ in. thick; ⅝ in. bolts with countersunk heads fasten the inner guides to the main sticks and at the same time secure the ironwork to the same. The bottom of the main guides are connected with the 12×12 bedpieces, shown in Fig. 3, by two timber-knees, and are tied at top by the cap shown in Fig. 6.

The dimensions and general arrangement of the back-bracing is fully shown in Figs. 1 and 3; the bolts used in this portion of the framework are ⅞ in. diameter. The side braces are round timbers 16 ins. diameter at the butt, and they are anchored to the hull by two heavy timber-knees to each. The bedpieces, as shown in Fig. 3, are fastened down to the hull by four bolts each 1 in. in diameter, the forward bolts passing through the 16×16 in. oak piece on bow, and the after bolts passing into a cross timber 6×14 ins., as shown at Fig. 4. The foot of the back-bracing is secured to the bed-timbers by one 1 in. strap-bolt in each timber, the strap portion of bolt being 2×½ in. in section. A ⅞ in. through bolt ties the three braces together.

The iron stayrods running from head of guides to after part of hull are two in number, and are each 1 in. in diameter.

The hoisting sheaves on top are two in number, placed side by side. They are 12 ins. in working diameter, 15½ ins. from out to out, and 3½ ins. wide; and the pin passing through them is 2½ ins. diameter at the sheaves, and 2 ins. diameter in the boxes. Experiences teaches that these proportions are none too great to stand the severe work frequently put upon it in hoisting heavy weights and tearing out timber. The fall-rope attached to the hammer is 2 ins. in diameter, and the "runner" used in hoisting up piles is 1⅝ ins. diameter.

The hoisting engine is a double-drummed Mundy engine of a nominal 25 HP.

Fig. 5 shows the hammer used with this machine. The drawing is sufficient to show its general design. The weight is 3,300 lbs.

Fig. 7 shows the method of attaching the two 5×12 in. horizontal braces to the round side braces, as further shown in Fig. 2.

(Many other illustrations of pile-driving machines will be found scattered through the volumes of Engineering News.)

BEARING PILES.

FORMULAS FOR THEIR SUSTAINING POWER, SIZE AND DISPOSITION IN ANY FOUNDATION.

Compiled by Rudolph Hering, M. Am. Soc. C. E.

There has been much uncertainty in the minds of many practical engineers regarding the proper formula for pile driving. Some text books and note books give only one agreeing with the views of the respective author; others give two or three without an impartial comparison. At best, the usual information is unsatisfactory, and it has been customary often to use an unreasonably high factor of safety, at the expense of economy, to guard against the uncertainties. In order to arrive at some intelligent judgment, the following has been gradually compiled. The original works and papers of the various authors on the subject were examined, and their formulas, experience and opinions extracted and compared. A portion of the matter is very simple, but as the simplest things sometimes do not appear evident when quickly wanted, it was thought well to add what was necessary to round off the subject for practical use.

There are two distinct classes of bearing piles. The first class consists of those which are driven to a perfectly solid foundation, and act as pillars or columns of support and which are therefore designated by the name Columns. The other class consists of such as derive their supporting power from the friction of the material through which they pass. These alone are properly called Piles.

As they require different theoretical considerations, they will be treated of separately, after some general notes applicable to both have been given.

Letters Denote:

Q (lbs) = Extreme load which a driven pile will bear, without sinking deeper into the ground, the last blow of the ram has sunk the pile s feet.

F (fraction) = Factor of safety used when loading a pile.

L (lbs.) = F × Q = Safe load which a pile can bear.

$\frac{L}{a}$ (lbs.) = Safe load which a pile can bear per sq. ft. of sectional area.

L_1 (lbs.) = Safe load on a test pile.

W (lbs.) = weight per sq. ft. upon foundation.

w (lbs.) = weight of the ram or hammer.

p (lbs.) = weight of pile.

h (ft.) = height of fall of the ram.

l (ft.) = length of the pile.

s (ft.) = distance which the pile sinks under the last blow.

s_1 (ft.) = distance which the test pile sinks under the last blow.

d (ft.) = distance from center to center of pile, if equal in both directions.

b (ft.) = distance from center to center of pile, if measured in a longitudinal direction.

c (ft.) = distance from center to center of pile, if measured in a lateral direction at right angles to b.

a (sq. ft.) = sectional area of the pile. In columns, a is the smallest sect. area; in piles sustained by friction, a equals the mean sect. area.

E (lbs. per sq. ft.) = Modulus of elasticity of the material of the pile. (This modulus is usually given in lbs. per sq. in.; it must, therefore, be multiplied by 144 when introduced in any of the following formulas) E = 1,600,000 × 144. will be sufficiently close for ordinary timber.

C (lbs. per sq. ft.) = Coefficient of elasticity, indicating how many lbs. per sq. ft. sect. area of the pile, will compress it to the limit of the elasticity of the material. (As this is also usually given per sq. in., it must be multiplied by 144 before being substituted in any of the following formulas.) C = 3,000 × 144 will be sufficiently accurate for ordinary timber.

I.—GENERAL NOTES.

1. **Weight of Ram and Height of Fall.**—Nearly all authorities say that a heavy ram with a short fall is much to be preferred to a light one with a long fall. Any increase of fall beyond 40 ft., even in the best machines, gave no increase of penetration in the sandy soil at the Brooklyn Navy Yard. Some authorities think, the weight of the ram should be in proportion to the sectional area, others to the total weight of the pile. Becker concludes from a theoretical examination that the most economical weight of a ram is equal to the weight of the pile. Ordinary, piles from 10 to 14 ins. in diameter are driven with rams weighing 1,200 to 2,000 lbs.

2. **Succession of Blows.**—It has been observed that quick blows with a heavy ram give a greater penetration at less expenditure of power than slow blows, with a light ram. In sand or silt, blows should follow rapidly in order to prevent the ground from settling around the pile before the next blow of the ram.

3. **Weight of Punch.**—Becker gives the most economical weight of a "punch" or "follower" as $\sqrt{(w + r)}$ lbs.

4. **Margin of Safety.**—On account of the many uncertainties in connection with piles, a wide margin of safety is recommended by all authorities, at least for important cases. It is sometimes impossible to tell how much of the sustaining is due to a "solid bottom," and how much to friction alone. There is often no guarantee that a pile will not steadily sink under a heavy quiescent pressure applied continuously and unremittingly, when it withstood perfectly a corresponding sudden blow of the ram. This may be feared especially in clays. The vibrations of the structure may in time produce unexpected settlements; this may also occur when certain clayey soils become very

wet adjoining the piles, and the friction is thereby lessened. On the other hand there are circumstances which tend to increase the strength after a lapse of time. The soil between the piles sometimes, especially if sandy, becomes more compact and increases the friction, and often the soil itself will carry a considerable portion of the weight.

5. Size.—It is the general opinion that piles should never be less than 6 ins. in diameter and rarely over 18 ins., and that the diameter should not be less than 5% of the length, unless the soil is very stiff.

6. Disposition.—Many writers give the nearest distance which piles should be apart, as 2½ ft. from center to center, because large piles especially when driven closely, will force each other up. Should this ever be feared, then the piles ought to be driven with the butt end down, commencing at the center of the area and working toward the sides. The ordinary distance is 3 ft. apart; for light work, it is from 4 to 5 ft.

7. Material.—Elm, spruce and oak are considered the best materials for piles.

II.—COLUMNS. SUSTAINING POWER.

Values for the safe load per square foot sectional area column, $= \frac{L_o}{a}$

Authority.	Values as given.	Values of $\frac{L}{a}$
Rankine and Mahan	1,000 lbs. per sq. in.... ..	144,000
Peronnet	786 to 990 lbs. per sq. in.	113.185 to 142,560
Storey	$\frac{1}{10}$ crushing weight of dry timber, viz :	
	Elm, 1,000 lbs. per sq. in.	144,000
	Ash, 860 " " "	123 840
	Beech, 800 " " "	115.200
	Spruce, 650 " " "	93,600
	Cedar, 610 " " "	87,810
	Oak, 600 " " "	86,400
	Yel. Pine, 533 lbs. pr sq.in.	77,472

As these values sometimes ascribe a much greater bearing capacity to the piles, than when bear, without sinking deeper into the ground, after friction alone is the supporting power, great care must be taken in applying them, remembering that they are only reliable when the piles act as columns and rest on a firm foundation. Careful judgment must be exercised as to whether this is entirely or only partially true, in which latter case a proper allowance must be made.

It should also be remembered that the columns rest on a pointed end only, which is an important consideration in "long columns." As the above values are safe crushing resistance of wood without regard to length of columns, they can only be valid, when the ground is sufficiently compact to prevent lateral bending of the piles; otherwise the reduction necessary for long columns will have to be made.

Formulas for maximum blows.—If the column has been driven to a perfectly solid foundation, the following formulas may be useful in ascertaining what weight of ram will be necessary for a given fall, or what fall for a given weight, to compress the material of the pile to its limit of elasticity, beyond which it should never be strained by the blow of the ram."

$$w = \frac{a\,l}{2\,h} \times \frac{C^2}{E}. \qquad h = \frac{a\,l}{2\,w} \times \frac{C^2}{E}$$

For most kinds of timber it will suffice to say:

$$w = 405\frac{a\,l}{h}. \qquad h = 405\,\frac{a\,l}{w}.$$

Formulas for Size and Disposition.—It is evident that each column of the sectional area a will have to sustain b × c × W lbs., or d^2 × W lbs., therefore,

$$a \times \left(\frac{L}{a}\right) = b\,c\,W = d^2\,W.$$

The following table gives the value of each factor.

Table for Size and Disposition of Columns.—Supposing columns to have any form of section but the same sectional area (a) and the same sustaining power:

Given sustaining power of column per sq. foot. $\left(\frac{L}{a}\right)$ = values according to various authorities as above.

Required sustaining power of column per sq. foot. $\left(\frac{L}{a}\right) = \frac{b\,c\,W}{a} = \frac{d^2\,W}{a}$.

Sectional area of column $a = \frac{b\,c\,W}{\left(\frac{L}{a}\right)} = \frac{d^2\,W}{\left(\frac{L}{a}\right)}$.

Weight on a square foot of foundation........................... $W = \frac{a\left(\frac{L}{a}\right)}{b\,c} = \frac{a\left(\frac{L}{a}\right)}{d^2}$.

Distance from center to center of columns measured longitudinally, $b = \frac{a\left(\frac{L}{a}\right)}{c\,W}$.

Distance from center to center of columns measured laterally at right angles to b, $c = \frac{a\left(\frac{L}{a}\right)}{b\,W}$.

Distance from center to center of columns if equal in both directions, $b = c = d = \sqrt{\frac{a\left(\frac{L}{a}\right)}{W}}$.

Example 1.—How close must spruce piles, 1 ft. square, be driven when resting firmly on solid rock, and therefore acting as columns, if they are to sustain with safety a weight of four tons per sq. foot?

Given: $a = 1;\ \left(\frac{L}{a}\right) = 93{,}600;\ W = 8{,}000.$

Sought: $d = \sqrt{\frac{a\left(\frac{L}{a}\right)}{W}} = \sqrt{\frac{1 \times 93{,}600}{8{,}000}} = 3.421$ ft.

Example 2.—What will be the proper sectional area of oak piles acting as columns in a rather soft ground, driven 3 ft. apart in one direction and 2 ft. 9 ins. apart at right angles to it; they are 30 ft. long, and the weight upon the foundation is to be 5,000 lbs. per sq. ft.?

Given: $b = 3;\ c = 2.75;\ W = 5{,}000;\ \left(\frac{L}{a}\right) = 86{,}400.$

Sought: $a = \frac{b\,c\,W}{\left(\frac{L}{a}\right)} = \frac{3 \times 2.75 \times 5{,}000}{86{,}400} = 0.477$ sq. ft.

corresponding to 9⅜ ins. diam., which is about $\frac{1}{40}$ of its length. A proper deduction for "long columns" must therefore be made. In this case $\left(\frac{L}{a}\right)$ would be about 25,000, which substituted gives:

$$a = \frac{3 \times 2.75 \times 5{,}000}{25{,}000} = 1.65 \text{ sq. ft.}$$

equivalent to 17¼ ins. in diam., or about $\frac{1}{25}$ of the length, which is sufficient.

III.—PILES.

Sustaining Power.

Unreliable Formulas.——All formulas developed from purely theoretical speculations regarding the resistance of the frictional surface of the pile in the ground vary greatly among themselves; they are also undesirable for other reasons, and have therefore been omitted here. All formulas containing coefficients for different qualities of ground are not given for the same reasons.

Reliable Formulas.—The only method which can be depended on in calculating the sustaining power of piles held by friction is the experimental one which introduces the actual distance (s) which a pile sinks under the last blow. The formulas developed in accordance with it and which are tabulated below, also differ very much as usually given, but when properly analyzed, classified and compared, they will enable the engineer to make an intelligent selection and obtain a perfectly satisfactory result. Tables I. and II. will facilitate such a rational comparison.

Contents of Table.—The first column contains the authorities, which are all of the best, mostly original, and all equally deserving of confidence.

The second column gives the value for s and answers the question: How far must a pile sink under the last blow in order to sustain a certain safe load?

The third column gives the safe load L which the whole pile will bear when it has sunk the distance s under the last blow.

The fourth column contains the factor of safety proposed by each authority. As it indicates solely a personal judgment, and has nothing to do with the formula itself, but mainly as it has caused large differences between some formulas, it has here been taken out and given separately. (Trautwine thinks ½ to 1-12 sufficient and Weisbach proposes 1-10 to 1-100!) It is true that several formulas could be made to agree better by introducing the factor respectively proposed by their authors. But for a rational comparison it was thought better to separate what is purely personal opinion from what is a derived formula.

The last column gives numerical values of extreme loads between the ordinary limits, (not considering the factor of safety). They will show the tendencies of the formulas and enable us to judge somewhat of their relative merits.

McAlpine's formula is evidently only reliable under the same conditions from which it was deduced, because in some cases it gives dangerous, in others impossible results.

Brix & Becker's second formula (neglecting the elasticity of the pile) seems unreasonably safe; as does also Nystrom's formula, when applied to light rams.

Trautwine's first formula cannot strictly be compared with the rest because s is neglected. Both give safer values for heavy rams and high falls than for light rams and low falls when compared with others.

The values of Rondelet, Rankine & Mahan give the sustaining power per square foot and not per pile as all other authorities. They are applicable when the piles will not move perceptibly under the last blow and can only be compared with the rest in a general way.

A comparison of factors of safety proposed by different authors shows a great variety of opinion.

The importance of this value of F in the formulas may be seen from the fact that all except one could be made to give the same result, merely by selecting factors of safety between ½ and 1-10. Therefore a judicious choice of value for F and an independent discrimination between the formulas themselves, seems necessary in order to obtain an intelligent result.

On the other hand, it appears by comparison that ⅙ to 1-5 would be a proper value of F for temporary or light work and 1-6 to 1-10 for permanent work, especially when subjected to vibrations. For very important work or in uncertain and unreliable ground, the safety should be increased still more, and left to the judgment of the engineer in each special case.

On the other hand, the formulas of Weisbach seem to offer the most practical solutions under the conditions to which they apply. When considering the compressibility of piles he obtains a little higher value than the general average, but still beneath that of Rankine. When the compressibility is neglected, he gives three cases;

(a) When w and p are comparatively large and L small, which rarely occurs.

(b) When w and p are small and L large, which is generally the case. This formula is the same that Mason developed and tested by a series of experiments.

(c) When p is neglected. This gives the sustaining power rather high values, but is commendable on account of its extreme simplicity, especially with a somewhat higher factor of safety. It is the same that Sanders developed and tested by an extensive series of experiments.

After a careful comparison the following formulas therefore seem to deserve the preference, as being reliable, safe and economical for general application.

CONSIDERING COMPRESSIBILITY OF PILE.

Weisbach:

$$s = F\frac{wh}{2L} \pm \sqrt{\left(\frac{F\,w\,h}{2\,L}\right)^2 - \frac{lwh}{2aE}};\ L = F\left\{\frac{wh}{s + \frac{lwh}{2asE}}\right\}.$$

NEGLECTING COMPRESSIBILITY OF PILE,

Weisbach and Mason:—

$$s = F\frac{w^2h}{L\,(w+p)};\ L = F\frac{w^2h}{s\,(w+p)}.$$

Simpler, though not quite as safe, is

Weisbach and Sanders:

$$s = F\frac{wh}{L};\ L = F\frac{wh}{s}.$$

FACTOR OF SAFETY FOR ALL THE ABOVE.

F = 1-3 to 1-5 for temporary or light work.

F = 1-6 to 1-10 for heavy work, especially when piles are held by clay and when they are subjected to vibrations.

F should be even smaller than 1-10 for very important cases or unreliable ground, and should be determined with reference to the circumstances of each case.

The exact value of F between the given limits must be determined by judgment in every special case. It will depend on the nature of the soil, the requirements of the structure, and on the general character of the whole work.

The value of L must never exceed the safe crushing resistance of the material of the pile, or $L \angle F \times a \times 144 \times$ crushing strength of material in lbs. per sq. in.

SIZE AND DISPOSITION.

Ratio of Sustaining Power to Frictional Surface.—McAlpine has stated, as one of the laws found by his experiments at Brooklyn, that, when piles of the same size are driven by the same hammer and from the same height of fall to different depths, their sustaining power is in the ratio of the squares of their fractional surfaces of penetration, or

$L : L_1$ = surface of friction^2: surface of friction$_1$

It does not appear whether any experiments were made with piles of the same length but different perimeters. However, as it is reasonable to expect the same results whether the frictional surfaces are increased by lengthening the pile or by giving it a greater diameter, we may assume, at least in all cases applying to ordinary pile driving:

$$L : L_1 = l^2 \times \text{perimeter}^2 : l^2 \times \text{perimeter}_1^2,$$

$$\text{or } L : L_1 = \text{perimeter}^2 : \text{perimeter}_1^2,$$

supposing the length of the pile to be equal.

Sustaining Capacity of Sections.—In the case of circular or square piles this would be equivalent to

$$L : \ _1 = a : a_1 ;$$

that is, the sustaining power is in direct proportion to the sectional area of round or square piles. In the case of rectangular piles, it follows (the ratio of the squares of the perimeters being greater than that of the areas) that they are more economical than round and square piles, provided all other things are equal.

The following table was arranged for values deduced from the formula:

$$L ; L_1 = a : a_1 ;$$

While this determins the size of the pile, the disposition is easily found by the following formula, which is evident from the consideration that one pile should sustain $b \times c \times W$, or

$$L = b\,c\,W = d^2\,W.$$

The following table, although simple, may yet be found convenient for quick reference:

Table for Size and Disposition of Piles.

Supposing piles to be round or square, of equal sectional area (a) and of the same length.*

Safe sustaining power of desired pile............L $= \frac{aL_1}{a_1} = bcW \qquad = d_2W$

* It is tacitly assumed that the ground is homogeneous. Generally this is not the case, but any difference can be adjusted by the depth to which the pile is driven, and therefore needs no factor in the table. It is only necessary to drive the pile until the value of a corresponding to the sustaining power L is reached.

Sectional area of desired pile... $a = \frac{a_1 L}{L_1} = bcW\frac{a_1}{L_1} = d^2W\frac{a_1}{L_1}$

Safe sustaining power of test pile............$L_1 = \frac{a_1 L}{a} = bcW\frac{a_1}{a} = d^2W\frac{a_1}{a}$

Sectional area of test pile ...... $a_1 = \frac{aL_1}{L} = \frac{aL_1}{bcW} = \frac{aL_1}{d^2W}$

Weight per sq. ft. upon foundation ....$W = \frac{aL_1}{a_1bc} = \frac{L}{bc} = \frac{L}{d^2} = \frac{aL_1}{a_1d^2}$

Distance from center to center of piles measured longitudinally... $b = \frac{aL_1}{a_1cW} = \frac{L}{cW}$

Distance from center to center of piles measured laterally .... $c = \frac{aL_1}{a_1bW} = \frac{L}{bW}$

Distance from center to centre of piles if equal in both directions ....$d = \sqrt{\frac{aL_1}{a_1W}} \quad \sqrt{\frac{L}{W}}$.

The relations of L to s or L_1 to s_1 (which is the same) are given elsewhere according to the various authorities.

Example 1.—How far apart should piles be driven in a certain direction, when at right angles to it they are 3 ft. from center to center; the weight to be sustained is 2,500 lbs. per sq. ft., the piles are 1 ft. square, and a test pile 8 ins. in diameter was driven until it sunk 1 in. under the last blow?

Given: $c = 3$; $W = 2{,}500$; $a = 1$; $a_1 = 0.35$; $s_1 = 0.08$.

Sought: 1. $L_1 = F\frac{wh}{s_1} = \frac{1}{10} \times \frac{500 \times 16}{.08} = 10{,}000$ according to Sanders' formula.

$$2.\quad b = \frac{aL_1}{a_1cW} = \frac{1 \times 10{,}000}{0.35 \times 3 \times 2{,}500} = 3.81 \text{ ft.}$$

2. If in the foregoing no test pile has been driven, but the permanent pile is to be driven until it will sustain a safe load of 30,000 lbs., then

Given: $c = 3$; $W = 2{,}500$; $a = 1$; $L = 30{,}000$.

Sought: $b = \frac{L}{cW} = \frac{30{,}000}{3 \times 2{,}500} = 4$ ft.

3. It is required to calculate the length of the piles for a certain foundation. They shall have a sectional area of 1 sq. ft.; are to be 3 × 4 ft. apart, and to carry a load of 3,000 lbs. per sq. ft. A test pile 6 in. in diameter is to be driven. As the lengths are considered equal in the above

table, it will only be necessary to find the length of the test pile driven under certain conditions, and estimate the permanent piles at the same length. Therefore the question resolves itself to finding the value of s_1 of the test pile, which will indicate how far it will have to be driven.

From Mason's formula we have

$$s_1 = \frac{F\,w^2\,h}{L_1\,(w + p)}.$$

Supposing $F = \frac{1}{8}$; $w = 1{,}000$; $h = 20$; $p = 150$; then

$$s_1 = \frac{2{,}898}{L_1}.$$

From the table we find

$$L_1 = b\,c\,W\,\frac{a_1}{a}.$$

Substituting the valves given above:

$b = 3$; $c = 4$; $W = 3000$; $a = 1$; $a_1 = 0.196$, then

$$L_1 = \frac{3 \times 4 \times 3000 \times 0.196}{1} = 7{,}036$$

and

$$s_1 = \frac{2{,}898}{7{,}056} = 0.41 \text{ ft., or about 5 ins.;}$$

that is, when the test pile is driven until it sinks not more than 5 ins. at the last blow, it will have reached a driven length equal to that of the required piles under the given conditions.

4. Required the sectional area of a pile which is to sustain safely a load of 30,000 lbs. A test pile has been driven to the same depth as that of the required pile; its sectional area is 0.25, and it has sunk a distance s_1 during the last blow, from which a safe sustaining power = 20,000 was calculated according to Weisbach's formula.

Given: $a_1 = 0.25$; $L_1 = 20{,}000$; $L = 30{,}000$.

Sought: $a = \frac{a_1 L_1}{L_1} = \frac{0.25 \times 30{,}000}{20{,}000} = 0.3625$

or about 9 ins. in diameter.

MISCELLANEOUS NOTES.

Among the many other articles besides those reprinted in this volume, which have appeared from time to time in Engineering News, the following may be noted as giving information likely to be particularly useful:

Oct. 8, 1887, "Pile-Driving by Electricity"; June 24, 1876, "The Gunpowder Pile-Driver"; July 9, 1887, "Extracting Piles at Poughkeepsie Bridge." To extract them (they were very long) they had to be driven down first to break the mud contact. The first three blows usually did not move them, but at the fourth blow they sunk about a foot, and could then be pulled out.

July 6, 1889, complete history of the early use of water jet for pile-driving.

June 25, 1887—Illustrations of the long splice used on the Poughkeepsie Bridge to get 130-ft. piles. The pile-ends were made octagonal and faced with eight 4 x 5 spruce splices, 20 ft. long, spiked on by ½ x 8-in. spikes, 1 ft. apart. The piles thus spliced could be slung horizontally, as if a single stick; 528 of them were used in 55 ft. of water, and loaded with 5 tons per pile. See also July 9, same year.

April 13, 1889—Long spliced piles (112 ft.) at Boston, 10 x 10 sticks 42 ft. long, spliced by banding at each end, inserting an iron plate, and exteriorly with four pieces of 2 x 10 oak.

May, 4, 1889—Instance of piles 166 ft. long, built up of three 60-ft. piles.

Aug. 16, 1890—Pile-driving and ditching plant of Omaha & St. Louis Ry., with details of cost of pile-driving. Average cost of pile in place, $5.14; of timber, only $3.60 (24 ft. x 15 cts.).

AN ECONOMICAL SHEET PILE DRIVER.

By Julian A. Hall, M. Am. Soc. C. E.

(From Engineering News, March 16, 1893.)

The accompanying sketch of an economical sheet pile driver is so simple that it explains itself at a glance. The machine was designed especially for coffer-dam work, but it can, of course, be used to put in sheet piling wherever such work is necessary. The method of operation is very simple. After the piles have been driven as deep as possible with a maul, the machine is used to drive them as deep as may be necessary. It is particularly adapted for use in rocky and sandy river bottoms, as it will quickly and cheaply jam the piles upon and between small boulders, and thus close openings that might otherwise cause a great deal of expense, trouble and delay.

The hammer is made of a section of an oak or other hardwood tree, squared or flattened, and of such size as may be necessary. Stout pieces of wood are bolted to the sides of the hammer, to hold it in the ways. Sufficient play should exist between the hammer and the ways to keep the hammer from jamming, and a like allowance should be made, for the same reason, between the ways and the pieces that hold the hammer between them. The machine should be built of sawed lumber, and inferior stuff will answer for the purpose as well as the best heart. The verticals may be made of 4-in. × 2-in. pieces, but for the other pieces lumber of a much less size will do perfectly well. The machine rests on 6-in. × 6-in. square stuff or anything handy about the work, and it is sufficiently light to be easily moved by two or three men with bars. To prevent toppling over in moving, it should be anchored bottom and top, fore and aft, with snub lines, which are payed out or hauled in, as may be necessary. From A, Fig. 1, the rope through the block passes over B, B, B, which are like rungs on a ladder, and on which men stand and pull the hammer up and let it fall. From three to six men are necessary, according to the size of the machine, and one of them keeps time in a sing-song tune, thus insuring unanimity of action. In a short time the men get the hang of the motion and lift the hammer with a small expenditure of force. Fig. 2 shows a piece of lumber, the size of a section of the piles to be driven,

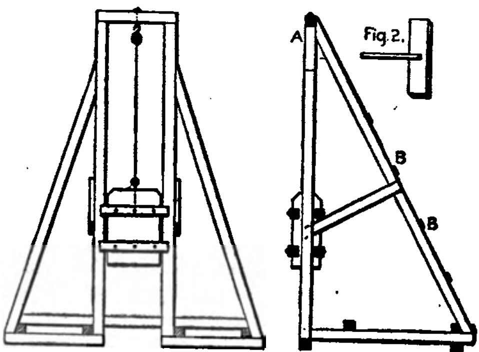


Fig. 1.

Sketch of Economical Sheet Pile Driver.

with a handle fitted into it. This is used to cause perfect penetration of such piles as go deeper than those adjacent. This is usually held by the gang boss, who watches the penetration and gives the word when to stop driving.

The principal points of advantage in the use of this machine are the cheapness, effectiveness and rapidity with which work can be done. It can be put up quickly and at very little expense, and when no longer needed the material can be otherwise used or abandoned, only the bolts, etc., being saved for the next job.

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INDEX.

The words "Pile," 'Pile-Driving," etc., have been avoided in this index, as it all relates to piles and pile-driving.)