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Reinforced Concrete Piles During Driving.

Das Verhalten von Eisenbeton-Pfählen während des Rammens.

Le comportement des pieux de béton armé lors du battage.

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Introduction.

In and around London there are many building sites where the ground consists of alluvial or made-up soil of very low bearing power for perhaps 10 ft. to 30 ft. from the surface. Below this a stratum of hard, compact gravel is to be found of varying thickness from perhaps a foot or two to 20 ft., a variation of this order occurring over any one site. Below the gravel a stratum of comparatively soft earth of low bearing power is again found and at a greater depth still a hard, compact clay is reached. In designing structures for such sites the engineers, owing to the uncertain thickness of the gravel belt, have in many cases thought it advisable to found below the gravel on the hard clay. In penetrating the gravel very hard driving conditions are experienced, and difficulties have been found in constructing precast piles of sufficient strength to withstand the very severe conditions. Typical examples of failures are shown in Figs. 1 and 2.

Before the commencement of the investigation very little information was available as to the effect of driving conditions upon the behaviour of the pile and no satisfactory method existed for determining the correct weight of hammer, height of drop or amount of head packing for a given pile. The rough rules provided by experience led to unsatisfactory results, and from the very limited knowledge available it was impossible to decide whether or not trouble would be likely to occur. For the engineers and for the contractors this state of affairs was very unsatisfactory. The Building Research Station was approached by the Federation of Civil Engineering Contractors and undertook to carry out an investigation into the behaviour of reinforced concrete piles with their collaboration.

The main problem of the investigation was, therefore, to devise methods of estimating the driving that a pile would stand without damage. This involved (1) an examination both analytically and experimentally of the nature and magnitude of the stresses induced in piles by impact, (2) a study of the effect upon impact resistances of the methods employed in the design and manufacture of the pile, (3) the development of methods of indicating dangerous conditions during driving. A full account of the investigation will appear as an official publication from the Building Research Station. An abridged account, rather fuller than that given in the present paper, has already appeared as a paper in the Journal of the Institution of Civil Engineers[1].

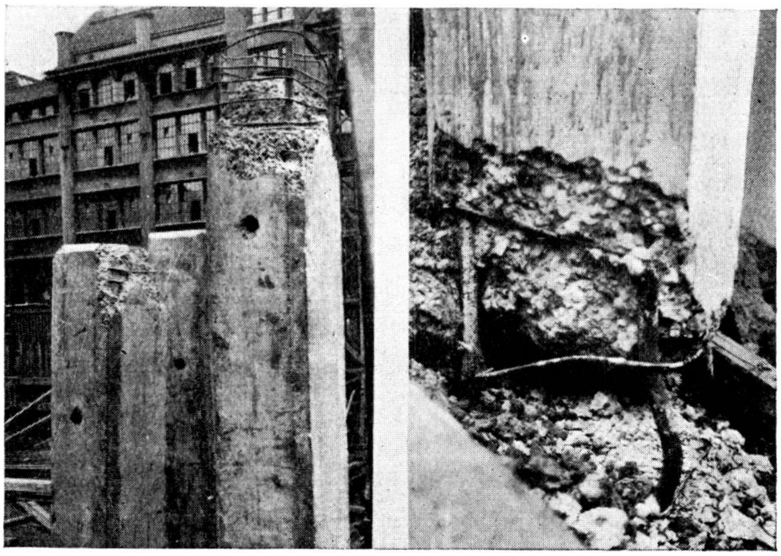

Fig. 1.
Examples of failure in reinforced concrete piles.

Theoretical Considerations.

General.

It is impossible within the scope of the present paper to attempt to give the full mathematical investigation that has accompanied the research. For a fuller account reference should be made to the Journal of the Institution of Civil Engineers[1] and to the Building Research Station publication.

Early in the study of the problem it was realised that useful representation of the conditions of pile driving could only be made on the basis of the wave theory of the propagation of stress in elastic rods. For the purpose of analysis the following assumptions are made: —

a) That the pile is undamaged when driven.
b) That the pile behaves as a linearly elastic rod.
c) That stress-waves in the hammer may be neglected.
d) That the dolly, helmet and packing are equivalent to a spring which will be referred to as the cushion, through which the compression is propagated instantaneously.
e) That the foot-resistance is elastic, the foot-pressure being proportional to the downward foot-movement. The method of relating actual cushions and foot-resistances to these ideal conditions is given later.

[1] „The Behaviour of Reinforced-Concrete Piles during Driving." By William Henry Glanville, D. Sc. Ph. D., M. Inst. C. E., Geoffrey Grime, M. Sc. and William Whitridge Davies, B. Sc. (Eng.), Assoc. M. Inst. C. E. (J. Inst. Civ. Eng., December, 1935).

The equation generally applicable to wave-motion in a long, thin, linearly-elastic rod has a general solution of the form

$$\zeta = f\left(t - \frac{x}{a}\right) + F\left(t + \frac{x}{a}\right),$$

where ζ denotes the displacement of the cross section from the initial position,
t ,, ,, time (after beginning of impact in this case),
x ,, ,, co-ordinate of any cross section measured from one end (the head of the pile),
a ,, ,, velocity of longitudinal waves in the rod.

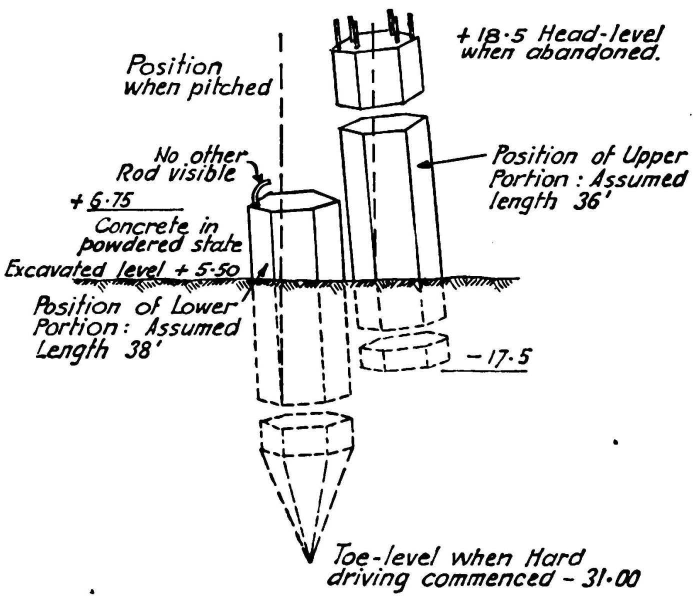

Fig. 2.

Failure at centre of pile.

The equation states that the displacement of any cross section is obtained by adding together two functions, the first of which, $f\left(t - \frac{x}{a}\right)$, represents a wave travelling down and the second, $F\left(t + \frac{x}{a}\right)$, a wave travelling up the pile. There is no wave in the upward direction until a time $\frac{l}{a}$ (where l denotes the length of the pile) has elapsed, that is, until reflection has taken place from the foot, and this wave will not reach the head until a time $t = \frac{2l}{a}$.

The equation which holds for the motion of the hammer during the initial period, $0 \leq t < \frac{2l}{a}$, before the reflected wave arrives at the head, has a simple solution, from which, with the aid of the assumed head-conditions, the displacement-function f representing the down-travelling wave can be determined for that interval. The function F, representing the reflected wave travelling up the pile, can then, from the assumption as to the character of the foot-resistance, be expressed in terms of the function f for a time $\frac{2l}{a}$ earlier. Hence, since f is known for the interval $0 \leq t < \frac{2l}{a}$, F will be known for the interval $\frac{2l}{a} \leq t < \frac{4l}{a}$. This procedure, applied to successive intervals $\frac{2l}{a}$, determines all waves travelling up and down the pile at any selected moment. By combining the waves at any point the displacement, and therefore the stress, may be found at any desired time t.

The theory leads to the conclusions that: —

1) The distribution of stress along a pile at a particular moment is, in general, not uniform.
2) The maximum stress at every point in the pile increases with increased stiffness of cushion.
3) The maximum stress at the head is proportional to the square root of the height of fall of the hammer.
4) For long piles, or for short ones with light hammers and stiff cushions, the maximum stress at the head is dependent only on the conditions at the head and is the same for all sets. The necessary condition for this is that the maximum value of the stress-wave travelling down the pile shall be attained before the reflected wave arrives from the foot.
5) The maximum stress at the foot depends upon the ground-resistance, being zero if the pile is unrestrained, or attaining a value twice that at the head if no movement is possible. In the first case a wave of tension, and in the second case a wave of compression is reflected from the foot.
6) In favourable circumstances, longitudinal vibrations are likely to be set up, in the same way as a musical note is evoked by striking the end of a steel bar. Theoretically, considerable tensions are possible, attaining a maximum at the midpoint of the length. They are likely to be of short duration, and to be followed immediately by compression.

The Head-Cushion.

The great influence of the head-cushion (the dolly, helmet and packing) in determining the stresses in the pile was shown early in the investigation. If no cushion were present between the hammer and the pile-head the stress at the head would rise almost instantaneously to a maximum. The head-cushion decreases both the rate of increase of stress and its maximum value. Stresses throughout the pile are similarly affected.

The stiffness of the head-cushion, denoted by k/A, is a factor to which reference will be made frequently. For an assumed head-cushion in which stress is proportional to strain, k is the usual stiffness-constant as applied to springs and is equal to the force required to produce unit compression, that is, $k = E'A'/l'$, where E' denotes Young's modulus of the dolly, A' its cross-sectional area and l' its length. If A denotes the area of the pile-head, k/A is, therefore, the stress on the pile-head required to produce unit compression, and is equal to Young's modulus divided by the length or thickness of the material, when the cushion is of the same cross-sectional area as the pile. It varies inversely as the thickness and is independent of the stress. The stiffness-constant for a hardwood dolly with a reasonably constant Young's modulus is obtained with sufficient accuracy from this expression. Helmet-packings, however, exhibit a non-linear relationship between stress and compression, and the appropriate value of $\frac{k}{A}$ depends upon the magnitude of the imposed stress. It is therefore necessary to specify $\frac{k}{A}$ as "at . . . pounds per square inch"[2].

If the dolly and packing have effective constants $\frac{k_1}{A}$ and $\frac{k_2}{A}$ then $\frac{k}{A}$ for the combination is given by

$$\frac{A}{k} = \frac{A}{k_1} + \frac{A}{k_2} + \cdots \frac{A}{k_n}$$

The cushioning effect is chiefly due to the packing beneath the helmet. The effect of the dolly is small, except in cases where the packing has been consolidated to such an extent that its stiffness has become very high, or where the dolly has become soft by brooming. The stiffness-constants $\frac{k}{A}$ of several types of head-packing have been deduced from the stresses recorded during the driving of test-piles and the results show that the value of $\frac{k}{A}$ for the packings used in practice may lie anywhere between 1,000 and 50,000 pounds per square inch per inch. Values as low as 1,000 pounds per square inch per inch. however, only apply to the first blows with new packing, and for practical purposes upper and lower limits of 10,000 and 50,000 pounds per square inch per inch may be used. The effect of the dolly is to reduce these values to about 9,500 and 40,000 pounds per square inch per inch respectively.

During the course of the investigation no form of packing was encountered which answered completely to theoretical requirements. These requirements are: —

1) Low stiffness, as represented by the factor $\frac{k}{A}$.
2) No increase of stiffness during driving.
3) Low cost in relation to durability.

Foot Conditions.

It has been stated that the assumption has been made in the theory that the foot resistance is elastic. In practice the only condition of elastic resistance is obtained when the set, as ordinarily measured, is zero. In all other cases the set may be divided into two portions; set, as ordinarily measured, which will be termed "plastic" set and the elastic movement of the earth, or "elastic" set. The set used in calculations has been designated the "equivalent elastic set" and has been taken as equal to twice the "plastic" plus the "elastic" set. The assumption that the work done at the foot, for the same maximum stress, is independent of the relative amounts of plastic and elastic set is implied. This assumption was tested theoretically by evaluating particular cases for a purely plastic foot

[2] For a fuller explanation of k/A see the Journal of the Institution of Civil Engineers,

and comparing the results with those obtained for a purely elastic foot giving a set equal to twice the set in the plastic case. The results of the comparison were in good agreement.

A typical figure for the estimation of maximum foot stresses is shown in Fig. 3. The complete series of figures covers a range of values of $\frac{kl}{EA}$ from 0.1 to 2.0. These figures furnish an upper limit to the foot stresses in cases of hard driving.

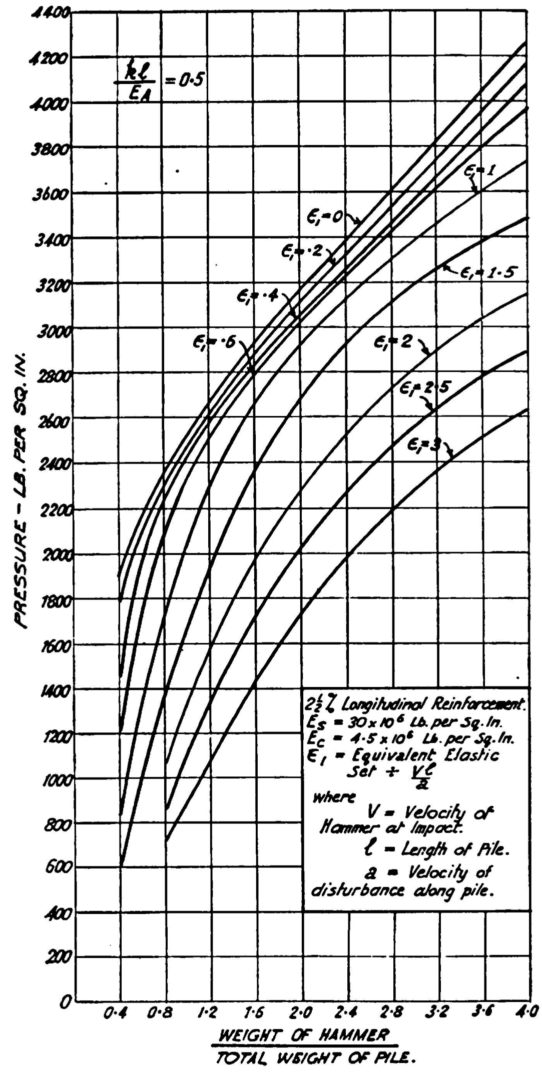

Fig. 3.
Maximum foot pressures for one foot drop.
For a drop of h feet multiply by $\sqrt{h}$).

General Description of Apparatus.

P i e z o - E l e c t r i c   S t r a i n - R e c o r d e r. The main requirement of a recorder for the short-duration impulses occurring in pile-driving is that all moving parts shall have a very high natural period of vibration, in order to follow accurately and without lag the motion investigated. This requirement led to the choice of a piezo-electric strain-gauge with a cathode-ray oscillograph: the natural frequency of the piezo-electric crystal unit may be made extremely high, so as to take full advantage of the inertia-less response of the oscillograph. Other desirable features possible with such a combination are that the gauges are sufficiently small to be embedded in the pile when cast and, by reason of their simplicity, are inexpensive enough to render their non-recovery from a test-pile of little consequence. The first apparatus constructed was used for tests at the Building Research Station, and has been fully described elsewhere[3]. A transportable outfit was built for the tests under contract conditions, embodying improvements designed mainly to reduce size and weight.

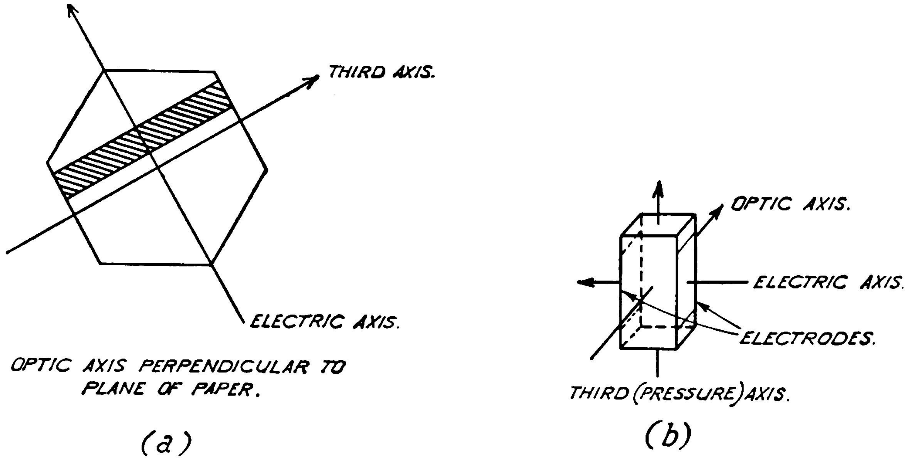

Fig. 4 a and b.

Position of axes in cut Quartz crystals.

The operation of the gauge depends upon the piezo-electric property of quartz, which, in common with certain other crystals, when compressed or elongated along one of the hemihedral axes, develops, at particular regions of the crystal, electric charges which are proportional to the applied force. Crystals, in the form of long rectangular prisms, are cut from the natural material in the direction shown in Figs. 4 a) and 4 b). The prisms, mounted in small watertight chambers, form the gauges which are cast in the pile at selected positions. When in use, the crystals are subjected to pressure along the "third" axis, and electric charges, proportional to the applied pressure, are liberated on electrodes attached to the faces perpendicular to the electric axis. Connection is made to the recording system by highly-insulated leads. A section of a gauge is shown in Fig. 4 c). The numbers denote 1) the quartz crystal, 2) the electrodes, 3) steel plates, 4) stiff spring, 5) heavy circular steel end-plates, 6) thin brass cylinder, 7) and 8) conical seatings, 9) the tube carrying the insulated lead.

When the gauge is assembled an initial load is put on the crystal by screwing up the adjustable seating 7; it then responds to tension as well as compression. In order that the gauge shall be strained to the same extent as the surrounding concrete, its dimensions are so chosen as to make its equivalent stiffness approximately equal to that of the concrete it replaces.

The arrangement of the strain recorder is shown diagrammatically in Fig. 5.

Set-Recorder. Sets have been recorded using the method shown in Fig. 6, which has given very satisfactory results. A board carrying a sheet of paper is firmly fixed to the front face of the pile by clamps. A straight-edge, along which

[3] G. Grime, Proc. Phis. Soc., vol. 46 (1934), p. 196.

a pencil is drawn to trace the set record on the paper, is nailed to a heavy baulk of timber, raised from the ground at either end by wooden blocks. The timber forms an effectively fixed base for measurement, since its vibration does not

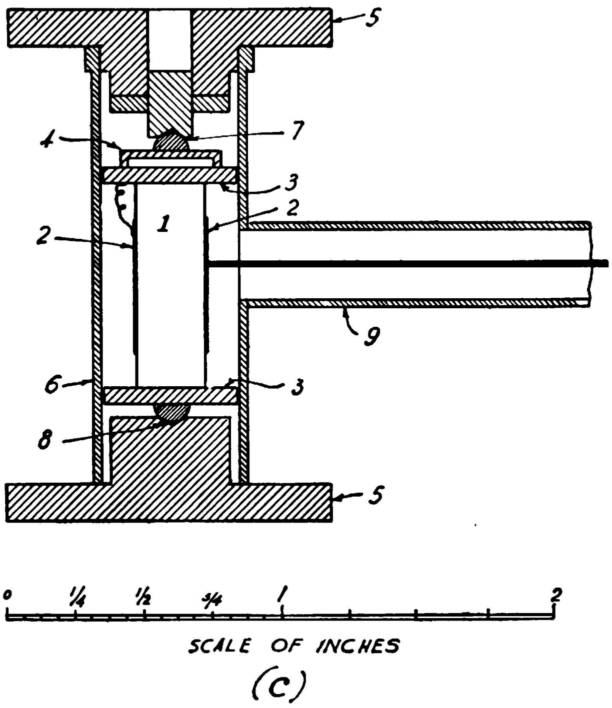

Fig. 4c.
Section of a gauge.

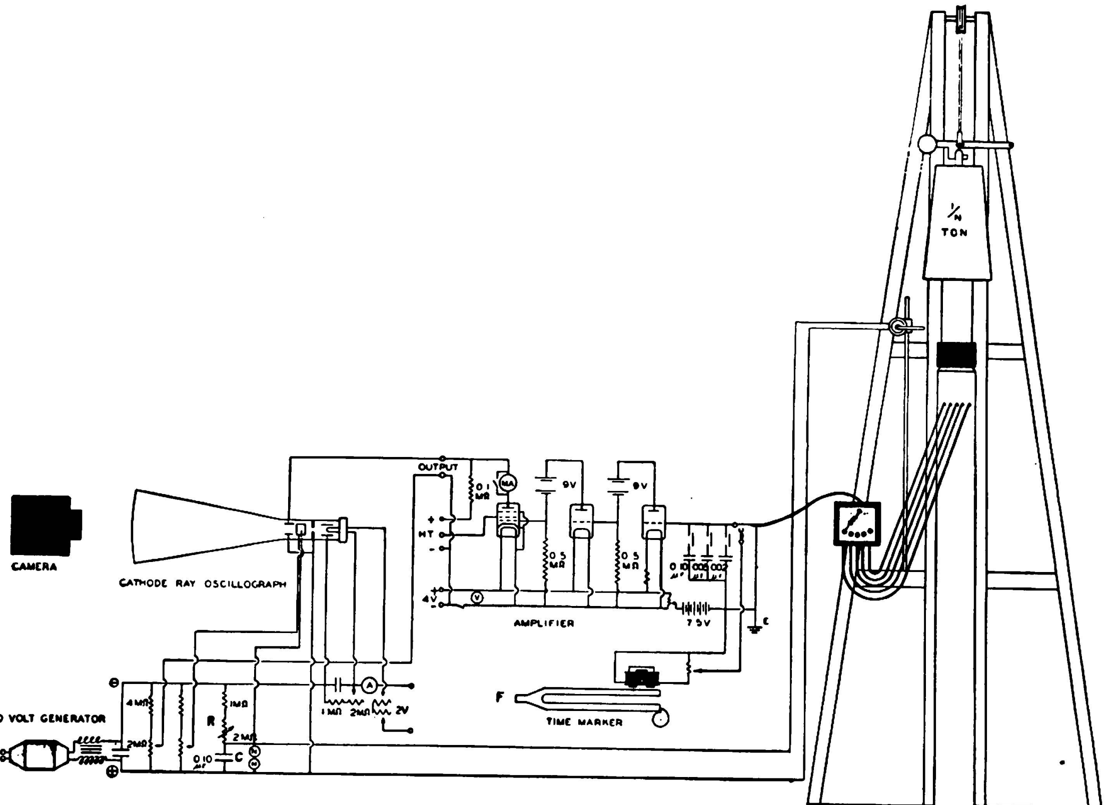

Fig. 5.
Electrical connections of strain-recorder.

become apparent on the record until after the set has been recorded, and is even then of small amplitude. From the record the permanent or plastic set and the elastic or recoverable set or earth-movement can be obtained.

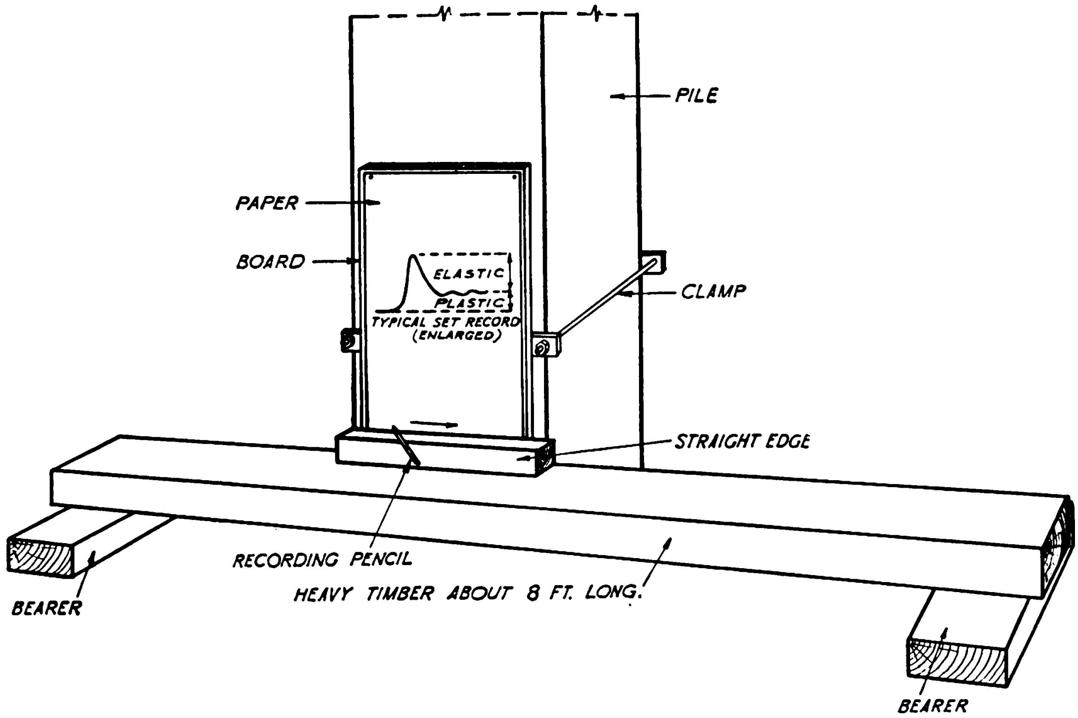

Fig. 6.
Set-recording apparatus.

Peak-Stress Indicator. A simple method of measuring the maximum stress at the head of a pile is provided by the use of a device for indicating when the maximum deceleration of the hammer exceeds a certain preset value. For, if the assumption that the mass of the helmet may be neglected, and the packing at the head regarded as a simple (not necessarily linear) spring, is approximately correct, measurement of the maximum deceleration of the hammer will enable the maximum stress at the head of the pile to be calculated very simply, for the force exerted by the hammer on the head of the pile at any instant = MF, where M denotes the mass of the hammer and F its deceleration.

Maximum-acceleration indicators have previously been used to indicate peak-values of the acceleration of road surfaces subjected to traffic vibrations[4]. The present instrument is somewhat different in construction, and is employed with a new method of visual indication. A mass m (Fig. 7) is held against an insulated stud I by a spring S, the compression of which can be varied by a calibrated screw C. Flat springs F ensure that any motion of the mass m is parallel with the pillars P. The assembly is mounted on the top of the hammer with the axis of the spring S vertical. An electric circuit is completed by the contact

[4] Report of the Permanent International Association of Road Congresses. VII th Congress, Munich, 1934. (2nd Section: Traffic.)

of the insulated stud I and the mass m, so that when the mass is pulled away from the stud the circuit is broken.

The indicating circuit, which is extremely simple, is also shown in Fig. 7. A dry battery of about 150 volts is connected to three resistances in series. Two of these are bridged by a small neon indicator-lamp, and one of the two

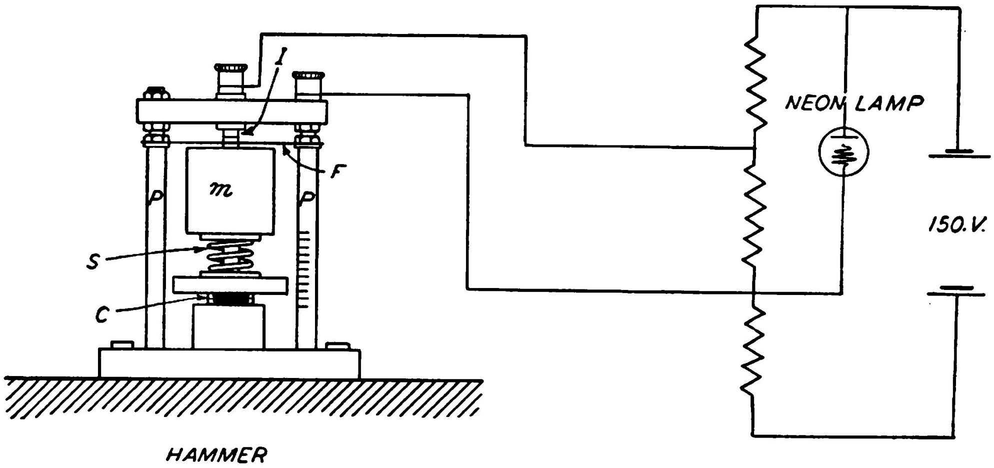

Fig. 7.
Peak stress indicator.

is normally short-circuited by the contact between mass and insulated stud. When the contacts are closed the voltage across the neon lamp lies between the flashing and extinction voltages, so that no current passes. When the contact is broken the voltage across the lamp, now that due to the potential drop across the two resistances, exceeds the flashing voltage and the lamp lights, remaining lit after the contacts close, since the voltage is still at a value higher than that necessary for extinction. This electric circuit is a very sensitive detector of the breaking of contact, and may be made to operate from a break of as little as 0.0002 second duration.

The tests carried out up to the present with the indicator have shown that head-stresses may be measured with a possible error of about 15 per cent.

Experimental Work.

I) Stress-Measurements. Following preliminary tests, which confirmed the general deductions from the wave-theory, experiments were carried out on piles driven into ground, under typically difficult contract conditions.

Details of the piles are given in Figs. 8. The ground conditions are shown in Figs. 9, on which the penetrations at which records were taken are marked.

The piezo-electric recording equipment, housed in a trailer, was operated at a distance of about 20 feet from the pile-driving frame. Connection was made to the gauges by lead-covered leads from 50 to 100 feet long.

The test procedure was essentially as follows for all the piles driven into ground: —

1) A record of the permanent set, averaged for a number of blows, was kept throughout the driving.

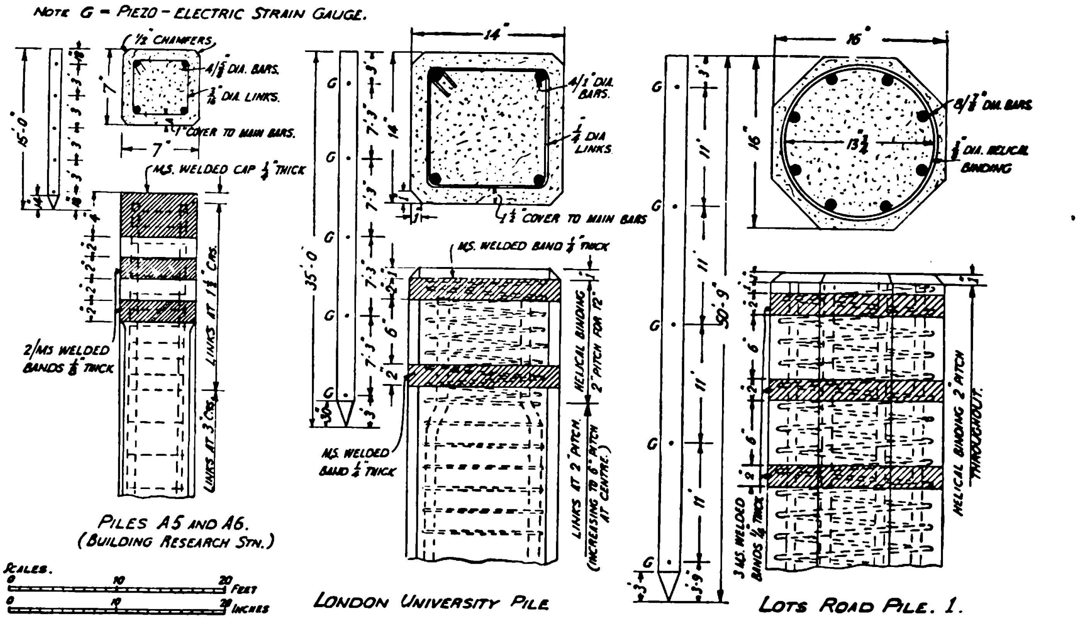

Fig. 8.

Pile details. (Head conditions).

Piles A5 and A6.

Drop-hammers weighing 480, 980 and 200 pounds, with trip release; head-cushion of four, twelve or twenty-four layers of felt initially each $^1/_4$ in thick.

London University Pile.

3 ton single acting steam hammer; 10 in. $\times$ 14 in. $\times$ 14 in. pynkadon dolly, 10 cwt. helmet, and packing of $3^1/_2$ in. of deal on top of 4 layers of sacking.

Lots Road Piles.

3.3 ton winch operated drop hammer; 9 in. cylindrical hickory dolly, 15 in. in diameter, 8 cwt. helmet, and packing of two layers of 2 in. manila rope and eight layers of sacking.

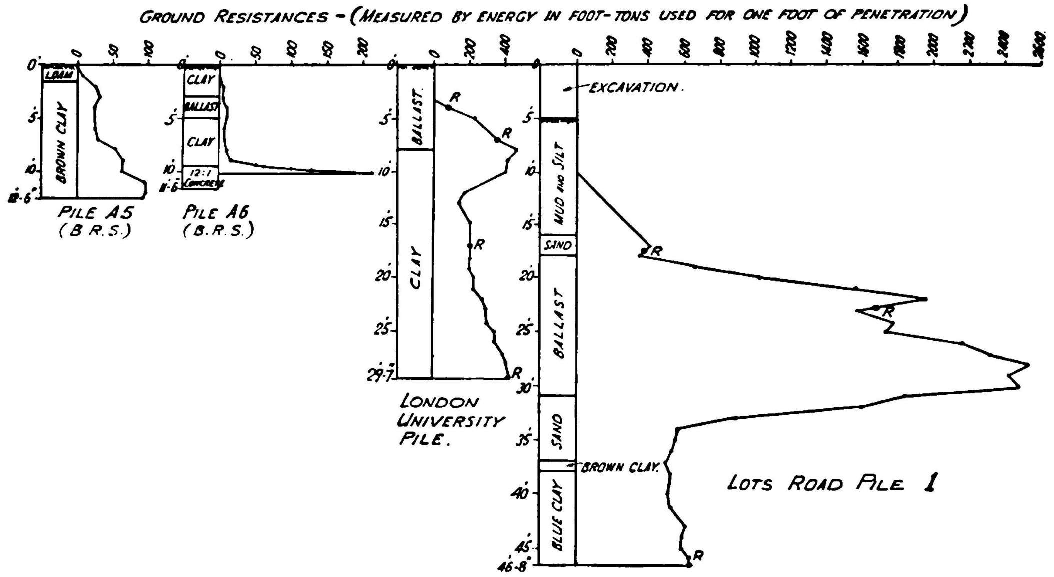

Fig. 9.

Ground conditions.

2) Stresses were recorded for several heights of drop of the hammer at four or five stages of penetration, the positions of which were decided by the ground-conditions (see Figs. 9).
3) Each set of stress-measurements was accompanied by the corresponding records of plastic and elastic set.

Various alterations and re-adjustments of packing material were made during driving, as necessity arose.

Typical records of strains measured with the piezo-electric strain-gauge are shown in Figs. 10, 11, 12 and 13. Their general characteristics agree with

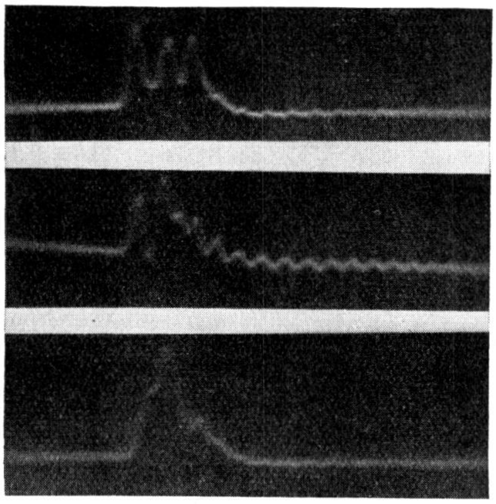

Fig. 10.

Record of the longitudinal vibration of a 15 ft. pile. Vibration frequency 455 per second.

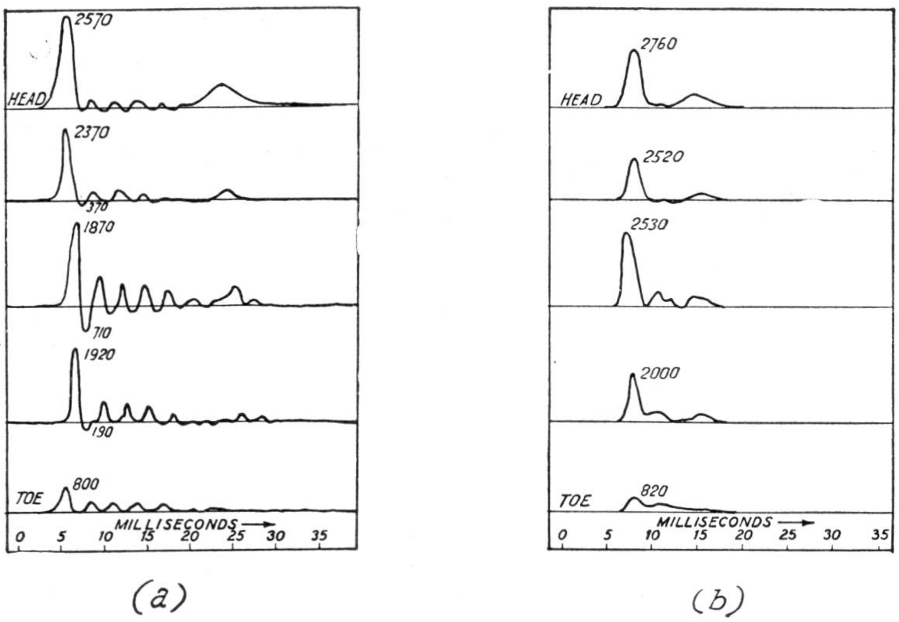

Fig. 11.

Records from a 15 ft. pile driven into stiff clay at the Building Research Station. Driving conditions: — four $^1/_4$ in. felts at head; 980 pound hammer; 24 in. drop. Penetration of point: — (a) 4 ft. 3 in., (b) 10 ft. Set: — (a) 0.55 in., (b) 0.08 in. Figures, indicate peak stresses in pounds per sq. in.

those predicted from the theory. The form of the stress-time curve and the maximum value of the stress vary along the length of the pile, in a manner depending on the ground-conditions. The duration of the record at the head is

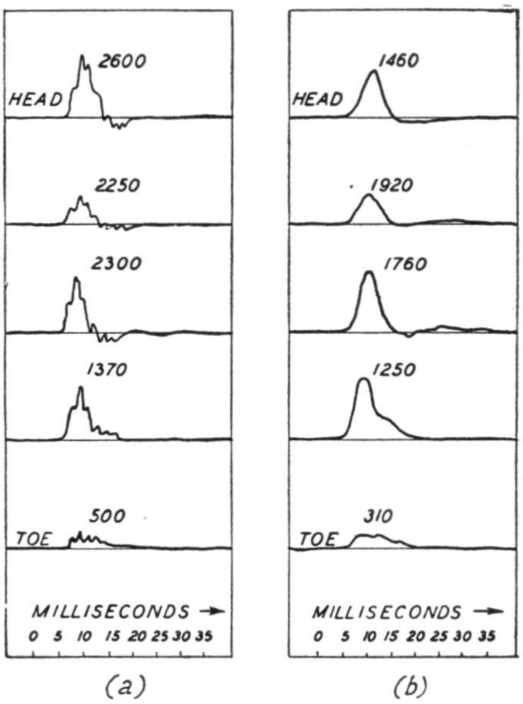

Fig. 12.

London University Pile; Typikal records. Driving conditions: — 3 ton hammer, 24 in. drops, penetration of point 29 ft. 6 in.; (a) contractor's packing with 10 cwt. helmet, (b) twelve felts without helmet. Set: — (a) 0.07 in., (b) 0.04 in. (Figures indicate peak stresses in pounds per sq. in. The low value at the head in (b) is due to back-pressure in the hammer).

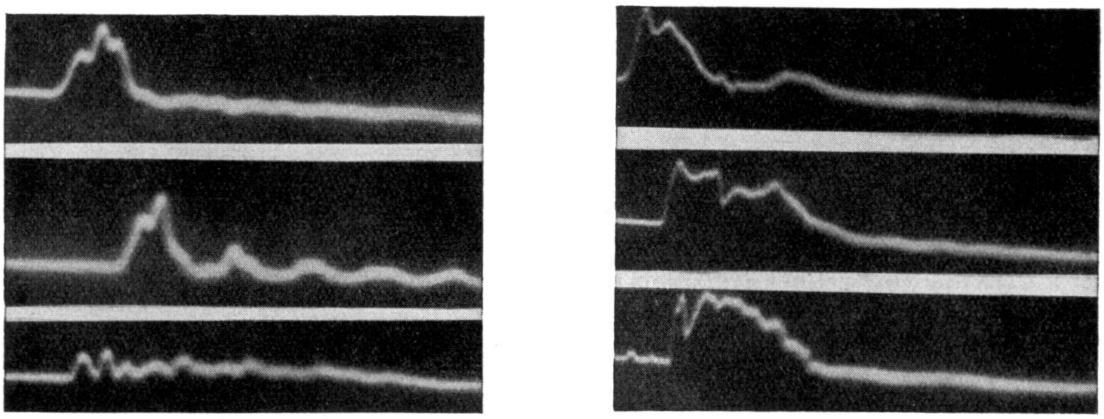

Fig. 13.

Lots Road Pile 2. Typical records for (a) easy and (b) hard driving. Driving conditions: — contractor's packing in 8 cwt. helmet; 3.3 ton hammer; drops (a) 24 in., (b) 36 in.; penetration of point (a) 14 ft., (b) 25 ft. Maximum compressive stresses: — (a) head 1590, middle 1400, foot 520 pounds per sq. in.; (b) head 1930, middle 2170, foot 2760 pounds per sq. in. Sets: — (a) 0.94 in., (b) 0.06 in. Duration of blow at head: — (a) 0.010 second. (b) 0.009 second.

generally of the order of 0.01 second; at the foot it may be greater. The prolonged vibration shown at the middle of the pile in Fig. 10 indicates that, under certain conditions, the pile may be made to vibrate longitudinally at its own natural frequency.

The Effect of Driving Conditions on the Stress in the Pile. In the majority of cases the highest compressive stress induced during driving occurs at the head of the pile. Only when the foot is being forced through an exceptionally hard stratum will it occur at the foot. This is illustrated by Figs. 14

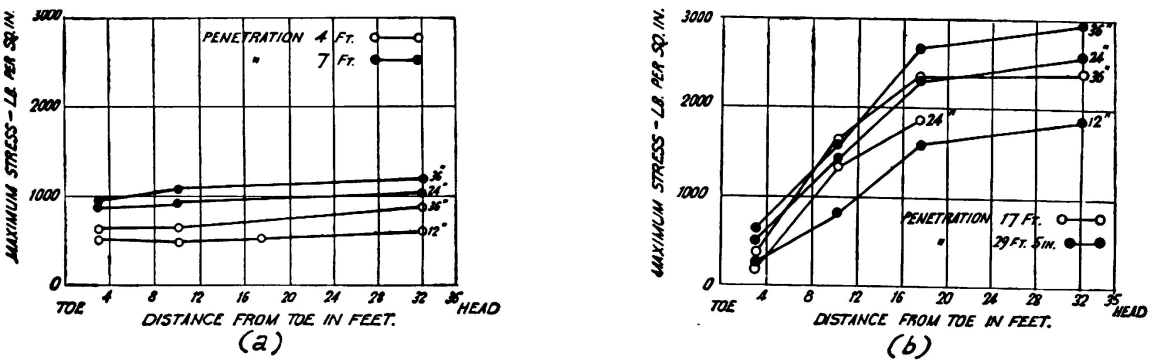

Fig. 14 a and b.

London University Pile.

Distribution of maximum compressive stress along pile at penetrations up to 29 ft. 5 in., with contractor's packing and helmet, and drops of 12, 24 and 36 in.

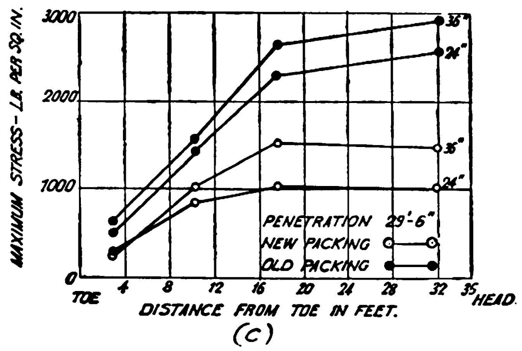

Fig. 14c.

Comparison of new and used contractor's packing for 24 in. and 36 in. drops.

and 15. From theoretical considerations it can be shown that the highest value of the maximum compressive stress must be attained either at the head or the foot, although in certain circumstances values only slightly lower may occur at other positions. At the middle of a pile stresses have been recorded equal to, or even occasionally greater than, those at the head, but these are within the experimental error of the stress-measurements. A comparison of some calculated and recorded head stresses is made in Fig. 16.

From elementary considerations it is apparent that the maximum head-stress for any given set of conditions increases with the weight of the hammer. The increase, however, is for normal head-stresses proportionately less than the increase in weight (see Fig. 16).

In giving an outline of the mathematical theory it has already been mentioned that, in consequence of the finite velocity with which the stress-disturbance travels, the maximum value of the stress at the head is in most cases independent of the ground-conditions and is determined only by the conditions at the head, that is, by the weight of the hammer, the height of drop, the area of the pile-

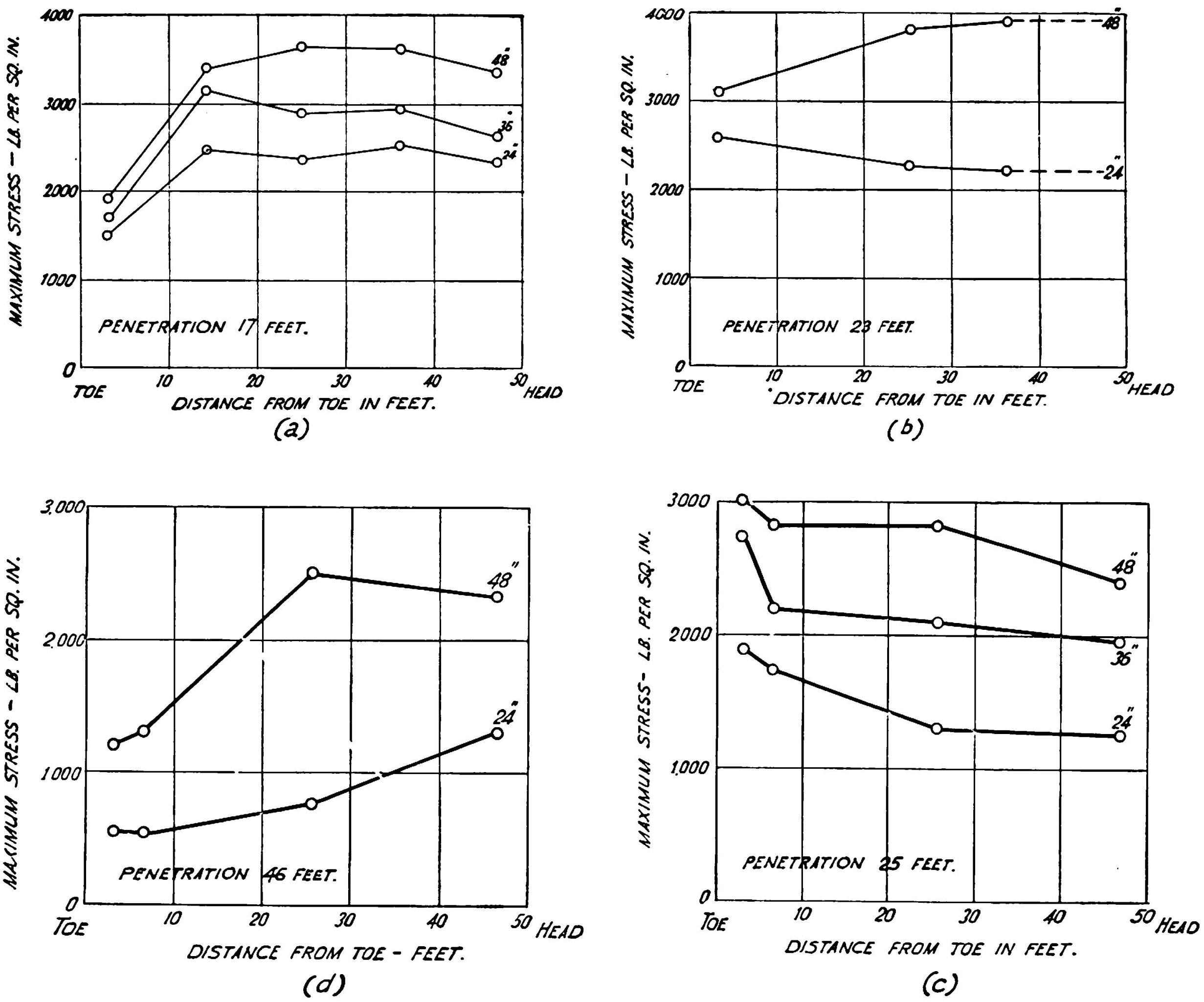

Fig. 15.

Lots Road Piles.

Distribution of maximum compressive stress along the pile at various penetrations, with contractor's packing and helmet, and drops of 24, 36 and 48 in. (a) and (b), pile 1; (c) and (d), pile 2.

head, the physical constants of the pile and the stiffness of the cushion. This is confirmed by experimental results.

A deduction of some importance from the foregoing is that if the packing has initially a high stiffness-constant, the head-stresses in the early or easy stages of driving may be nearly as high as at later stages when the driving is hard.

The advantages of a low stiffness-constant k/A will be dealt with when considering the effect of driving conditions on set. The important effect of an increase of stiffness during driving was demonstrated most convincingly during one of the tests at the London University site, where the softwood packing showed an increase of stiffness which resulted in an increase in the stress at the head of the pile of 100 per cent. (Fig. 14 c).)

Dangerous local concentrations of stress may result from unevenness in placing the packing material on the pile-head. An instance of this was met during the driving of the first Lots Road pile, where the head, which had withstood thousands of blows without sustaining any damage, failed immediately after the insertion of fresh packing. The failure was definitely attributable to the uneven distribution of the packing, which had slipped towards the back of the pile.

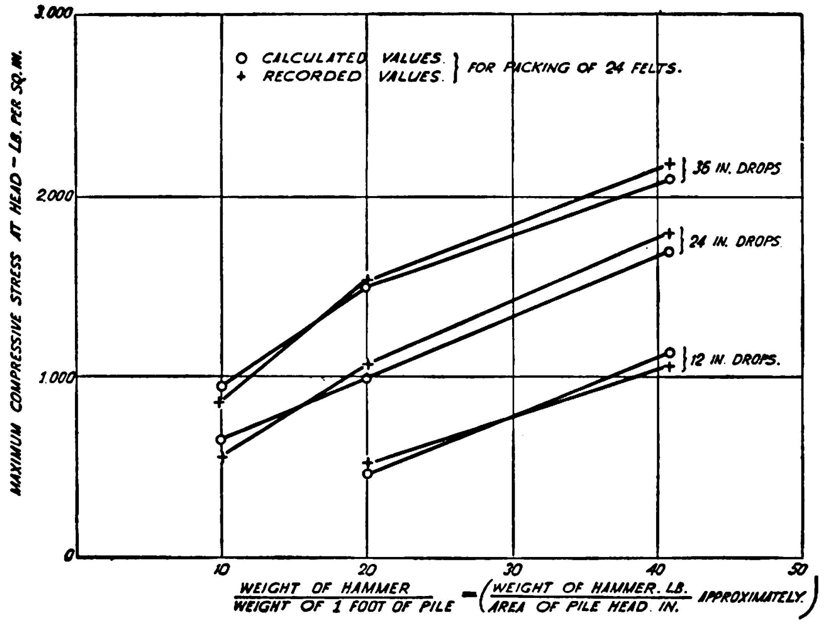

Fig. 16.

Calculated and recorded head stresses for 15 ft. piles.

Experimental evidence (Figs. 12) shows that with packing alone at the head of the pile the stress-time curves, particularly at the head, are smooth in form; with a helmet, the form of the record at the head is that of a vibration of high frequency superimposed on a smooth curve. The helmet may be regarded as a mass supported between two springs, the dolly above and the helmet-packing below. The high frequency appearing in the record is due to the oscillation of the mass on the springs. The magnitude of the maximum stress is in most cases affected little by these oscillations, which are very quickly damped out.

A considerable length of the upper portion of a pile may be subjected to maximum stress almost as great as that at the head. This occurs when no interference from the reflected wave takes place, the only decrease being that due to dissipation of energy by internal and skin friction. The 50-foot Lots Road piles provide examples, the maximum stress along the upper half of the pile remaining approximately constant (Figs. 15). In such cases compressive failure may commence at some distance below the head if a region of weakness exists owing to damage in handling, inadequate transverse reinforcement, or poor concrete.

The stress at the foot depends to a large extent on the set, small sets producing high stresses and vice versa. The foot-stress only becomes important under conditions where its maximum value is likely to equal or exceed that at the head, assuming head and foot to be of equal strength.

The stresses recorded during the driving of test-piles under practical conditions show that only in the case of piles driven on one site, and that one of exceptionally hard driving, were the head-stresses exceeded. (See Fig. 15 c.) Here the foot-resistance was due to a layer of ballast 13 feet thick, and was such as to require two to four hundred blows per foot of penetration.

Calculated and recorded values of the foot stresses are set out in Table I, and in every case the calculated figures are higher by 20 to 30 per cent, than those recorded. It therefore appears probable that the effect of skin-friction and propagation-loss is not negligible, even in such extreme cases of high foot-resistance.

Table I. Comparison of Calculated and Recorded Foot-Stresses.

Pile	Weight of hammer. Pounds	Height of drop. Inches	Packing	Equivalent elastic set. Inches	Maximum foot-stress Pounds per square inch.	
					Calculated	Recorded
Building Research Station (15 ft.)	980	12	12 felts	0.17	1,700	1,300
		24	„	0.39	1,950	1,670
		36	„	0.42	2,860	2,000
	2,000	12	„	0.19	2,440	1,780
		24	„	0.52	2,800	2,230
Lots Road (No. 1)	7.400	24	Contractor's	0.26	3,300	2,600
		48	„	0.45	4,0C0	3,100
(No. 2)		24	„	0.23	2,660	1,900
		36	„	0.34	3,300	2,760
		48	„	0.41	3,950	3,040

Tensile stresses of short duration but considerable magnitude, occurring in the middle portion of the pile, are theoretically possible. This was recognized at an early stage of the investigation and was then considered as a possible major cause of failure below ground. The results of stress-measurements on piles driven under practical conditions, however, do not support this view.

The results show that to set up high tensile stresses the pile must be free to vibrate at its fundamental longitudinal mode, with anti-nodes, that is, places of maximum motion and minimum stress, ot its ends. To fulfil these conditions the ground-resistance must be low and the head-conditions such that the hammer rebounds early and leaves the head free; that is to say, a hard packing and a light hammer must be used. As far as the experimental knowledge goes the evidence is against the occurrence of tensile stresses under practical driving conditions. It is interesting to note that no sign of failure in tension was observed during the driving of the 15 foot test-piles at the Building Research Station, altough tensile stresses greater than the tensile strength of concrete were recorded.

A series of charts given in Figs. 17, 18 & 19 enables any particular piling-conditions to be examined to ascertain whether maximum stresses of 3,000 lb.

per square inch or 2,000 lb. per square inch are likely to be exceeded during driving. Three conditions of head-cushion have been included, namely, soft, medium and hard. For all types of packing tested the hard condition has been found to apply after about 1,000 blows.

From Fig. 17 the ratio of the weight of the hammer and helmet to the weight of one foot of pile is first obtained. From Fig. 18a) or 18b), depending on whether 2,000 or 3,000 lb. per square inch is selected as a maximum for working conditions, the effective height of fall is obtained for the particular conditions of head-cushion required. This effective height of fall is then converted to the

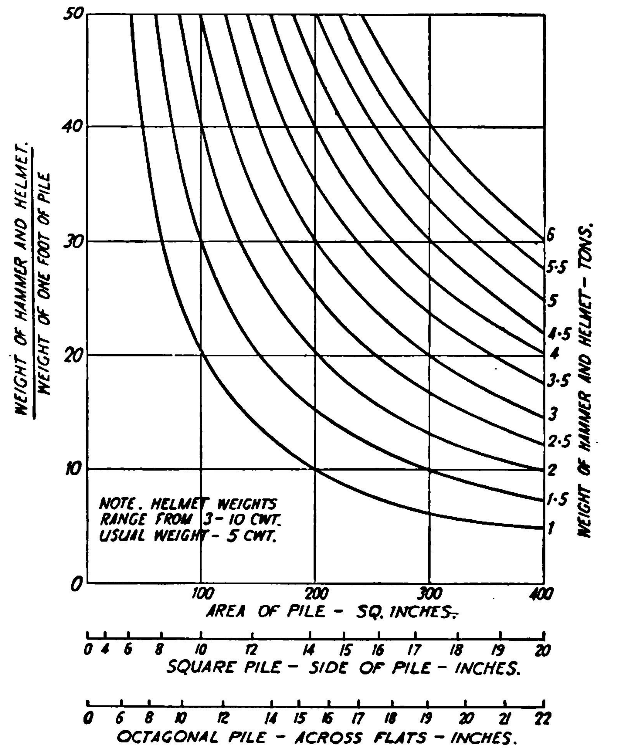

Fig. 17.

Diagram giving the ratio $\frac{\text{weight of hammer and helmet}}{\text{weight of 1 ft. of pile}}$

(Weigth of reinforced concrete taken as 160 pounds per cu. ft.)

height of free fall by means of Fig. 19. Any height of fall greater than this will produce a head-stress greater than that selected.

Figs. 18a) and 18b) also enable the equivalent elastic set which produces a similar stress at the toe, that is, either 2,000 or 3,000 lb. per square inch, to be obtained. Equivalent elastic sets lower in value and falling below the curve produce higher stresses. For foot stresses an allowance of 30 per cent, has been made for friction.

The Effect of Driving Conditions on the Set of the Pile. In the course of the investigation a considerable amount of information has been obtained on the effect of driving conditions on set. It is widely recognized that the energy-efficiency of driving increases with the weight of the hammer used.

The results of the tests are in agreement with this. They also show that the effect is less marked for easy than for hard driving.

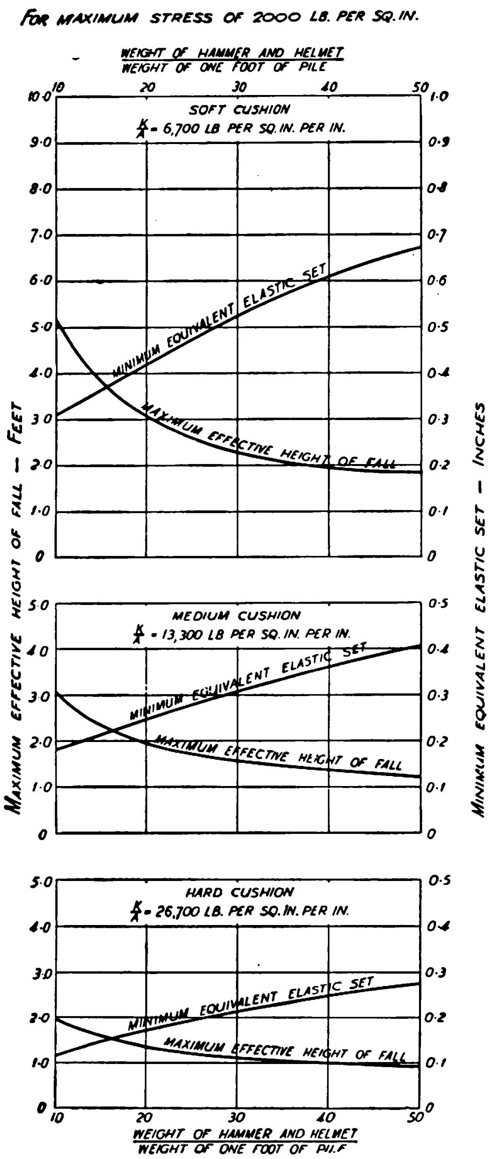

Fig. 18b.

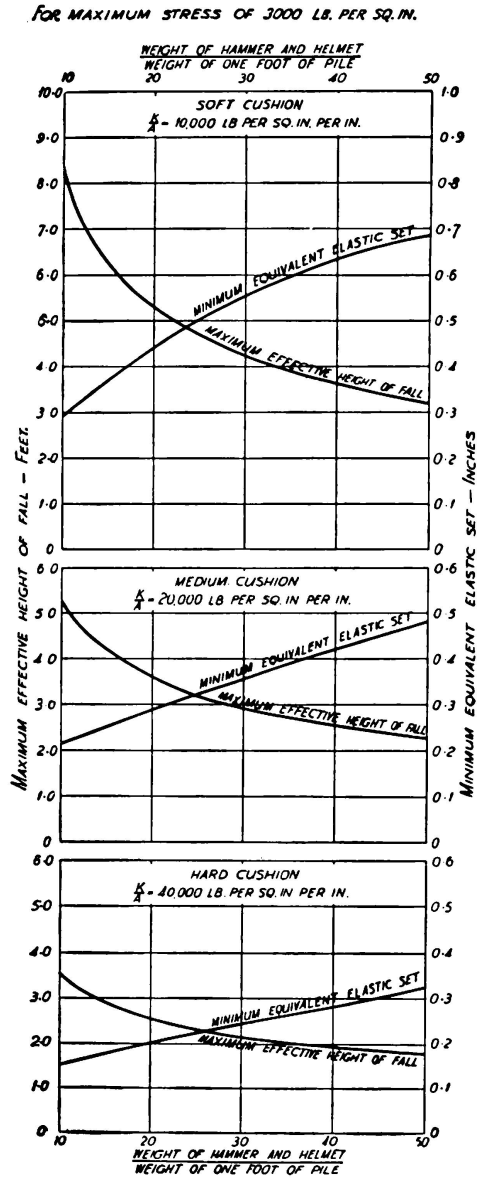

Fig. 18a.

Relation between the ratio $\frac{\text{weigth of hammer and helmet}}{\text{weight of one foot of pile}}$ and the effective heigtht of fall and minimum equivalent elastic set for maximum stress of 3,000 lb. per sq. in. ($2^1/_2$% longitudinal reinforcement in pile. Young's modulus for concrete $4.5 \cdot 10^6$ lb. per sq. in.).

The use of a heavy hammer has another advantage at least as important as that of energy-efficiency. Theory and experimental evidence show that, when the heights of drop are adjusted so as to give the same maximum head-stress, the set increases with the weight of the hammer.

The stiffness of the head-cushion has been shown to have an important effect on stress; its effect on set is also considerable, with the important difference, however, that the effect on set is much more dependent on ground-conditions.

Within the range investigated the energy-efficiency of a hammer is found to be greatest when the stiffest packing is used, the gain of efficiency increasing with hardness of driving. For example, the energy-efficiencies of 480 pound and 980 pound hammers used to drive a 15 foot pile through soft clay were practically unaffected by replacing the packing of four $^1/_4$ inch felts by one of twenty-four felts. For moderately hard driving, however, an appreciable decrease of energy-efficiency accompanies a reduction in the stiffness-constant. Again, it was observed that when, during the last stages of the driving of the 50 foot Lots Road piles, test-blows were delivered using thicknesses of twelve and twenty-four felts as packing, the sets for a particular drop were in every instance greater with twelve than with twenty-four felts.

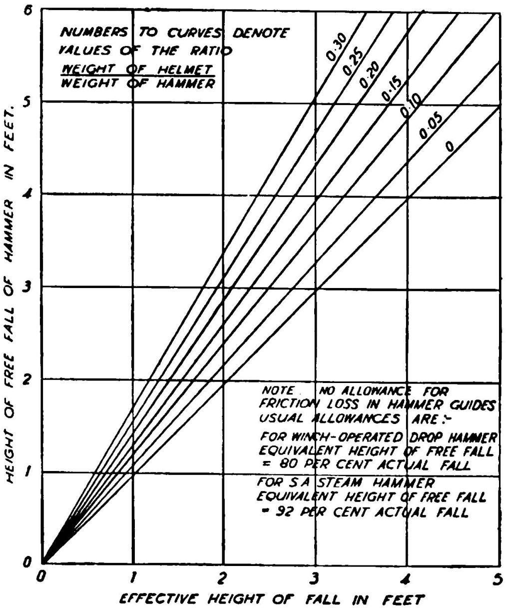

Fig. 19.

Conversion of effective height of fall to height of free fall of the hammer. Numbers to curves denote values of the ratio: $\frac{\text{weight of helmet}}{\text{weight of hammer}}$. Note: No allowance for friction loss in hammer guides usual allowances are: — For winch-operated drop hammer equivalent height of free fall = 80% actual fall. For S. A. steam hammer equivalent height of free fall = 92% actual fall.

This effect is important in connection with the probable accuracy of the bearing capacity of a pile as determined from test-blows. It is widely recognized that no bearing-capacity formula can be expected to be of general application, and that the successful use of any formula is largely dependent on the ability of the user to make appropriate allowance for ground- and driving-conditions. It is obviously of advantage to reduce the number of factors for which allowance has to be made; and since the energy-efficiency of a blow decreases with reduction in the k/A value for all except easy driving conditions, it is of the greatest importance that the packing used for the test-blows should be in as standard a condition as possible. The use of a standardized form of packing for this purpose would obviously be the ideal, but in the light of present information it is difficult to suggest a suitable form in which a packing could be standardized. Failing such a material it would appear better to use well compacted than new packing. Well compacted packing will ensure the maximum set for a given height of drop and does not depend so much on the type of material used as new packing.

The greatest set for a given maximum head-stress is produced by the use of the packing of lowest stiffness. It is clear that this must be so for easy driving, since the energy-efficiency is practically unaffected by packing stiffness whilst the maximum head-stress is dependent on it. Fig. 20 demonstrates the effect

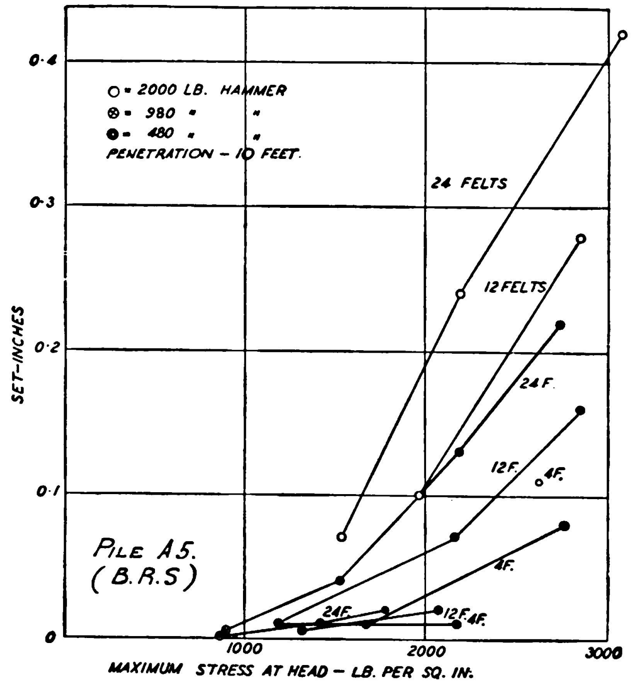

Fig. 20.
Variation of permanent set with maximum head stress for 15 ft. pile.

for moderate driving and, although there is no experimental evidence for hard driving, theory indicates that in this case also the maximum set for a given head-stress is obtained by using the packing of lowest $\frac{k}{A}$ value.

Another observation of considerable importance is that the efficiency of driving, particularly in hard driving, increases with the maximum head-stress attained; in fact with hard driving drops less than a certain height cause no permanent set. During the driving of a 50 foot pile at Lots Road, at the penetration of 41 feet 6 inches the permanent sets for drops of 24, 36 and 48 inches with the same head-cushion were 0.04, 0.10 and 0.19 inch respectively.

It is therefore particularly important in hard driving that for efficient set-production the head of the pile should remain undamaged, as the maximum stress that can be sustained by a damaged pile-head without progressive disintegration is always considerably less than the maximum for a sound head.

The Most Favourable Driving Conditions. The most favourable driving conditions may be defined in two ways: they may be either those conditions which produce the greatest set for the least expenditure of driving energy, irrespective of the stresses induced in the pile; or those conditions which produce the greatest set for the lowest stresses in the pile, irrespective of the energy expended. Since in most cases protection of the pile from failure is the first consideration, and the amount of energy expended, within reasonable limits, is of minor importance, favourable driving conditions will be considered as those enabling a reduction of driving stresses to a minimum.

Within the range of conditions investigated it has been shown that the most favourable conditions of driving, represented by the value of the factor $\frac{\text{set}}{\text{maximum head-stress}}$ occurred without exception when the heaviest hammer was used in conjunction with the head-cushion of lowest stiffness, and that there is reason to suppose that this rule can be applied generally and is virtually independent of the type of ground into which the pile is driven.

Under certain conditions of moderate and hard driving the use of a head-cushion of low stiffness involves a loss of energy-efficiency. In few cases, however, is the loss likely to be of sufficient magnitude to justify the employment of a stiffer cushion, since in most piles the margin of strength would not be large enough to permit an appreciable increase in driving stresses. It appears, therefore, that modifications of driving equipment to obtain better driving conditions should be such as to increase the duration of the blow and reduce the maximum value of the stress.

The Peak Stress Indicator. The instrument may be used for two purposes, fistly to measure the maximum stress at the head of the pile at a particular stage in the driving and, secondly, to indicate, by the lighting of the neon-lamp, when the maximum stress at the head exceeds a certain predetermined value. From the value of the maximum head-stress it is possible to determine 1. the packing constant $\frac{k}{A}$, and 2. an approximate value of the impact-strength of the concrete, by measuring the maximum head-stress at the greatest height of drop that can be used without head-failure.

It is clear that, when set to indicate any maximum head-stress above a predetermined value, the instrument acts as a danger-signal in respect of head-stress, giving warning when the height of drop should be reduced or new packing placed in the helmet.

II) Tests to Destruction. In addition to the tests already described a large number of 15 ft. piles has been tested to destruction. For this purpose the piles were driven against a heavy concrete block using a packing of a suitable type at the foot in order to obtain any desired condition of toe resistance. The piles were 7 in. square and a hammer weighing 980 pounds was used.

The factors investigated were as follows:—

1) Amount and disposition of reinforcement.
2) Type of cement and age at test.
3) Cement content.
4) Curing conditions.
5) Type of aggregate.

A full description of these tests will be found in the papers to which reference has already been made. The conclusions are included in the following section of the paper.

Summary of Conclusions.

1) Stress Conditions. The work, both theoretical and experimental, has shown that the wave-theory of the propagation of stress applies during the driving of reinforced concrete piles. The compression due to the blow travels down from the head and is reflected from the foot as a compression for hard or a tension for easy driving. The stress at any point is the sum of the stresses due to the down- and up-travelling waves. During hard driving compressive stresses may exceed 3,000 lb. per square inch.

The cushion at the head of the pile, that is, the dolly and the packing in the helmet, plays an important part in determining the stresses; the softer the cushion, the lower the maximum stress. For a cushion with a linear stress-strain relation the stiffness-constant (k/A) is the stress on the pile-head to produce unit compression. Cushions usually have a non-linear stress-strain relation and therefore k/A must be defined at "at... lb. per square inch". At 3,000 lb. per square inch values of k/A range, in practice, from 10,000 to 40,000 lb. per square inch per inch and at 2,000 lb. per square inch from 6,670 to 26,700, k/A being approximately proportional to stress. Most forms of packing harden during driving. With piles of length greater than 30 feet the maximum stress at the head is generally independent of the conditions at the foot of the pile.

For very easy driving conditions, that is, with very large sets, the compressive stresses at the toe will be very low and the stress-wave will be reflected as a tension, which when combined with the downcoming compression-wave produces tensions which increase from zero at the toe to a maximum towards the middle of the pile. No failures due to these tensile stresses have been observed. As resistance at the toe increases the compressive stress increases and may theoretically reach twice the value of the maximum head-stress. Values 50 per cent. greater have been recorded.

The foot-stress depends on the total movement of the toe, that is, the set as ordinarily measured and the elastic earth-movement at the toe. For the purpose of stress-estimation the ordinary or permanent set has been termed the "plastic" set and the earth-movement the "elastic" set. When combined, as follows, they have been called the "equivalent elastic set".

Equivalent elastic set

= twice plastic set (or permanent set as ordinarily measured)

+ elastic set (or earth-movement).

The worst conditions at the foot are obtained where the whole of the resistance to penetration is concentrated at this point. Friction at the sides of the pile will have only a small effect on head-stresses but may have an important influence in reducing the stresses below ground.

A simple method of set measurement is satisfactory (see Fig. 6). A correction to the elastic set is necessary to allow for the elastic compression in the pile. This is 0.004 inch per foot of pile embedded where the maximum head-stress is 3,000 lb. per square inch, and 0.003 where the stress is 2,000 lb. per square inch. Further investigation of the order of the elastic and plastic sets occurring in practice is required.

Charts have been prepared enabling the stresses to be deduced for a wide range of conditions.

The best conditions of driving are obtained by using the heaviest possible hammer, together with the softest head-cushion (lowest stiffness k/A), the height of drop being adjusted to give a safe stress. It is suggested that a reasonable minimum value of the ratio weight of hammer/weight of 1 foot of pile would be 30. This gives for 12 inch, 14 inch, 16 inch and 18 inch square piles hammers of $2^1/_4$, 3, $3^3/_4$ and $4^3/_4$ tons respectively (see Fig. 17).

In nearly all cases the equivalent elastic set increases practically in proportion to the hammer-weight, and experimental evidence shows that the plastic set (set as ordinarily measured) increases at a greater rate.

The head-stress may be determined from the peak-stress indicator which is attached to the hammer and measures its deceleration. Alternatively, the instrument may be used to indicate when any predetermined value is exceeded. Measurement of the elastic and plastic sets enables the stress-values thus determined to be used to obtain foot-stresses. Figs. 17, 18 and 19 may be used for this purpose where the indicator is adjusted to 2,000 or 3,000 lb. per square inch.

2) Practical Consideration. To put pile-driving on a proper scientific basis an improved form of head-cushion is required possessing the qualities of permanence and of low and constant stiffness. No entirely satisfactory helmet-packing has yet been discovered, and it is possible that a mechanical device to take the place of the dolly, helmet and packing will afford the most satisfactory solution.

The margin of safety in driving reinforced-concrete piles is frequently so low that slight carelessness in the manufacture and driving of the pile may be sufficient to cause failure. The head of the pile should be carefully formed, and all surfaces in the helmet should be truly plane and at right angles to the axis of the pile. It is most important that the helmet-packing should be placed evenly on the pile-head, and that the layer immediately in contact with the head should be of soft material covering the whole surface. The fall of the hammer should be parallel with the long axis of the pile, and the blow should be delivered as nearly concentrically as possible.

The impact-strength of concrete may be as low as 50 per cent. of the crushing-strength. For a working-stress of 3,000 lb. per square inch a concrete of crushing-strength of not less than 6,000 lb. per square inch is therefore necessary, and for 2,000 lb. per square inch not less than 4,000 lb. per square inch.

To obtain strengths greater than 6,000 lb. per square inch proportions not leaner than $1:1^1/_2:3$ (nominal), that is, 1 cwt. of cement to $1^7/_8$ cubic foot of sand and $3^3/_4$ cubic feet of coarse aggregate, should be used, and the greatest care exercised in the selection of aggregates, the control of water-content, and curing. (It is of interest to note that a crushing-strength of only 3,300 lb. per square inch is required for $1:1^1/_2:3$ High-Grade concrete under the Code of Practice.) For easier driving conditions, where the lower crushing-strength is adequate, that strength might be obtained by careful control with a 1:2:4 mix.

Curing-conditions have a very marked effect on impact-strength, and piles should be cured under damp conditions as long as practicable. Unless conditions of driving are easy it is recommended that this period should be not less than 14 days. Further information is required on impact-strength and on the factors influencing it.

Longitudinal reinforcement does not affect the impact-strength greatly. The amount of lateral reinforcement, on the other hand, profoundly affects the impact-resistance of a pile, particularly at the head and toe. It is recommended that for a length from the extremities of $2^1/_2$ to 3 times the external diameter of the pile the volume of lateral reinforcement should not be less than 1 per cent. of that of the gross volume of the corresponding length of pile. The diameter of the ties should conform with the usual practice for reinforced concrete, and should be not less than $^3/_{16}$ inch or one-fourth of the diameter of the main bars, whichever is the greater. The minimum spacing of the ties at head and foot should be such as to provide ample facility for placing the concrete. It was observed on an outside contract that the performance of piles reinforced with heavy spirals ($2^1/_4$ per cent.) was definitely good, and although patches of surface spalling occurred, they did not materially affect the resistance of the pile to further driving.

External head-bands placed in the mould before casting the concrete considerably strengthen the pile-head.

The dependence of the set produced on the packing conditions indicates the importance of specifying the condition and nature of the packing to be used in determining the sets on which bearing-capacity is estimated. Failing a standard packing it should at least be specified that the packing shall be well compacted, thus ensuring the maximum set per blow. Up to the present the research has not been concerned with with the bearing-capacity of piles as such.

Summary.

Engineering contractors have frequently experienced great difficulty in complying with specifications demanding that reinforced-concrete piles should be driven through a hard stratum to a set in a lower layer, and in such circumstances many piles have been shattered not only above but below ground. The paper is an abridged account of research carried out at the Building Research Station with the main object of discovering means of estimating when conditions of driving are likely to be destructive to the piles. The work was done with the assistance and collaboration of the Federation of Civil Engineering Contractors.

The research has involved the measurement, by a piezo-electric method, of the strains occurring in the piles during driving. A description is given of the piezo-electric recorder employed. It was found that the strains were profoundly affected not only by the ground conditions, but also by the conditions at the head, and particularly by variations in the amount and state of the head packing.

A mathemathical theory is outlined which enables the stresses to be estimated for certain conditions of head packing and of set. The theory is shown to agree reasonably well with the actual measurements made, not only in small-scale tests but also in tests made under conditions of hard driving on typically difficult sites. The greatest stresses are shown to occur at the head or the foot, and charts are given which enable the stresses at these positions to be estimated.

Conclusions drawn from tests to destruction on 15 ft. × 7 in. × 7 in. piles are also given, and recommendations are made for the manufacture and treatment of piles before driving.