Discussion.

Mr. GEOFFREY GRIME gave three demonstrations of the experimental methods employed by the Authors. A model pile made of rubber-latex, cement and sawdust was used to reproduce waves of the form which occurred in ordinary piles. That special concrete was employed in order to slow up the speed of travel of the waves, so that a small model would exhibit effects similar to those observed in a full-sized pile. For the first demonstration a peak-stress indicator was screwed to the hammer, and the height of the hammer raised by steps of $\frac{1}{4}$ inch until the peak-stress indicator came into operation, which was shown by a neon lamp, so that the peak-stress then attained at the head of the pile could be determined. Mr. Grime.

The second demonstration related to the effect of the foot-conditions. On the head of the pile there were two thicknesses of felt, and in the first case a hard rubber buffer was placed under the foot, so that the pile was being driven under comparatively hard conditions. First the head-stress and then the foot-stress was shown on an oscillograph, and it was seen that the latter was much greater than the former. A soft packing was then substituted under the foot, representing easy driving conditions, and it was shown that the duration of the foot-stress was now much greater and its maximum value considerably smaller.

For the third demonstration a hard packing was used instead of the felts at the head of the pile and a soft packing at the foot, and the oscillograph record was seen to spread out on both sides of the zero line, indicating that both compression and tension were set up in the pile.

Dr. R. E. STRADLING said he was grateful for the opportunity of expressing before The Institution the thanks of the Building Research Station to the Federation of Civil Engineering Contractors for the support, both financially and by constructive criticism, which had made possible the carrying out of the work outlined in the Paper. The investigations had been carried out with the general guidance of a co-operative committee consisting originally of Messrs. G. M. Burt, Assoc. Inst. C.E., G. G. Lynde, M. Inst. C.E., and A. Melville and officers of the Building Research Station, but in the later stages the assistance was obtained of Sir Leopold Savile and Mr. G. B. R. Pimm, MM. Inst. C.E. Dr. Stradling.

It was realized that there were many problems remaining in engineering practice which required scientific investigation, but he

Dr. Stradling. would suggest that they were all very difficult ones, or they would have been solved long ago. The solution of such problems as that discussed in the Paper required the co-operation of the man with practical experience and the scientific worker; and not only of one scientific worker but of a group. In the present case the Building Research Station received the advice of the Radio Research Station as to the best way of employing the cathode-ray oscillograph and associated devices. The Paper described work which had resulted from the whole-hearted co-operation of practising engineers, research engineers and physicists, and it seemed to him that only by such co-operation could reasonable advance be made in the applied sciences.

He did not propose to discuss the Paper in detail, but he would like to draw attention to two questions which were still awaiting solution. The Authors had shown in their work that the impact-resistance of concrete could be judged only as being between the approximate limits of 50 and 80 per cent. of the crushing strength. As such a lack of exact knowledge meant a possible variation of the factor of safety between 1 and 1·6, and since most pre-cast piles were driven with a very low factor of safety, the difference between those limits often meant the difference between failure and success. It was thus a matter of some urgency that the impact-strength of concrete should be very fully investigated.

The other point which he would like to emphasize was the importance of the measurement of the elastic set during driving. The bearing-power of a pile was usually calculated on the so-called "set," namely, the plastic set or permanent sinking of the pile during the last few blows of driving. The work described in the Paper had shown that the elastic set was of importance in the determination of stresses during driving, but it was of equal importance in relation to the bearing-capacity of the pile, for, when driving took place in soft ground, the plastic set would be much greater in relation to the elastic set than when driving in hard ground. One case at least was known where trouble had occurred through ignoring that important fact. If the elastic movement had been taken into account, the driving would have been carried on to a much greater resistance.

That consideration of future work led him to the point at which he would like to take the opportunity of expressing to last year's Council of The Institution his deep appreciation of the steps which had been taken to make the Research Committee of The Institution a really live body, and to the Committee itself for the support which they were proposing to give to the continuation of the work under a co-operative scheme. Further, on behalf of his colleagues and himself, he would like to express to The Institution their thanks for the opportunity provided by the present Meeting of bringing the work done before The Institution for discussion. The work had really only been started, but it was of the greatest value to those engaged in it to obtain the criticism of The Institution while the work was actually in progress, and not to have to wait until the end. Dr. Stradling.

Sir HENRY JAPP remarked that he greatly admired the ingenious methods adopted to determine the effect of hard driving on piles. The information given in the Paper did not confirm the statements made by manufacturers of reinforced-concrete piles, who claimed that the pile would carry the load required so long as the demanded set were obtained. That was emphasized in one advertisement by a very striking picture of a blindfolded man, but he thought the Authors had partly taken away the blindfold, so that something could be seen of what took place in the pile beneath the surface. Sir Henry Japp.

A few years ago, the firm with which he was connected had to drive some 1 : 2 : 4 *ciment fondu* piles of from 70 to 80 feet in length. They were octagonal in section, 17 inches across the flats, and reinforced with eight $1\frac{1}{8}$-inch bars wrapped on the Considère system with $\frac{5}{16}$-inch wire. The minimum age of the piles when driven was 3 days, but most of them were 7 days old. A 6-ton monkey was used for driving with a fall of 3 feet 6 inches, the set specified being $\frac{1}{2}$ inch for ten such blows. Not only were the piles specified to be driven to a definite set, but also to a definite depth, about — 53·00 O.D., so that the shoes would be below the Port of London Authority's final dredged river-bed level. At about — 32·00 O.D., some 50 feet below the surface, the piles struck a ledge of "Blackwall rock," or "cemented gravel" as it was called in America, and many of them fractured. Ultimately, after breaking quite a number, it was decided to pull up in the Blackwall rock, provided that a hundred consecutive blows did not give a penetration of more than 4 inches, but, if the rope broke or anything interrupted the operation, another hundred consecutive blows had to be given.

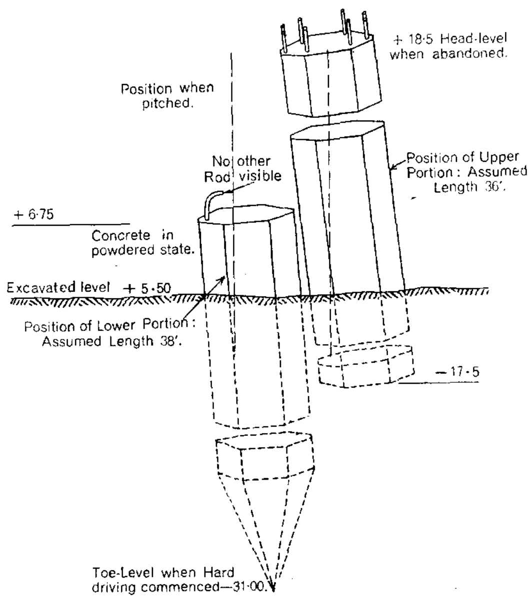
Fig. 2 (p. 151) showed the usual form of fracture; the concrete crumbled, the pile lurched to one side, and ultimately the reinforcing broke and the upper portion of the pile went on penetrating. Some of them came to a set on the Blackwall rock. *Fig. 23* (p. 206) showed a 74-foot pile which broke, the upper part then continuing on its journey. *Fig. 24* (p. 207) was a remarkable example of telescoping. The pile pulled up on reaching Blackwall rock. It then received further hard driving, and was passed as having reached a set of 4 inches in a hundred blows. It was cut off in 5-foot lengths as the excava-

Sir Henry Japp.

tion proceeded, until the contractors found to their amazement that instead of eight $1\frac{1}{8}$-inch rods there were sixteen, so they went deeper and found what had taken place. It served to illustrate the difficulty of knowing what was going on under the ground. If excavation had ceased a few feet higher up, the pile would have been assumed to be satisfactory.

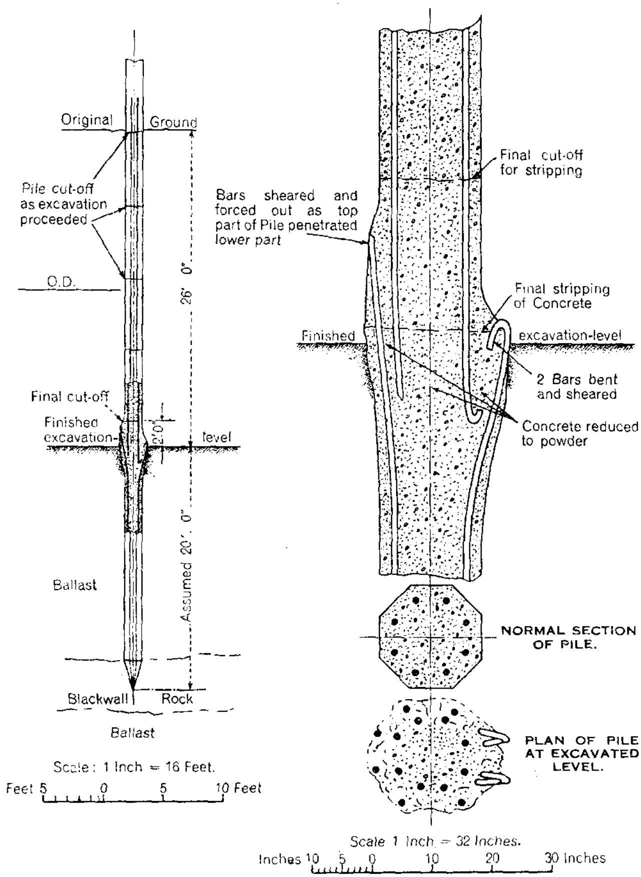
As a practical man who had to drive the piles or to induce other people to drive them for him, he found some difficulty in reaching

Fig. 23.



definite conclusions from the Paper which might be applied in a practical way in order to reduce the cost of driving piles. The result of the projected series of tests on packing materials would be of considerable interest, as the consumption of such materials was quite an expensive item. For instance, in the case mentioned, over ten thousand sacks and 600 cubic feet of pynkado were consumed in driving two thousand piles. In trying to penetrate the Blackwall rock the pynkado in the helmet often caught fire owing to the heat generated by the blows of the monkey. A slow rate of driving of about 18 blows per minute was finally adopted for those long piles to help to reduce the wear of the wire bonds and the swaying of the tall pile-frames, which were 90 feet in height. That probably, though unintentionally, allowed the vibrations in the pile to die down, and the driving was less damaging to the pile than would have been the case had the normal rate of blows per minute been used. Sir Henry Japp.

Fig. 24.



Mr. R. Travers Morgan proposed to confine his remarks to the piles which had been driven and were still to be driven at the London University site. In that case there was rather the reverse of the usual conditions, in that the piles were driven through the ballast first and then into softer material below. The difficulty at first Mr. Morgan.

Mr. Morgan. found on that site was that of repeated breaking of the heads, and it was found that whether the pile was seven days old with rapid-hardening cement, or fourteen days, a month, two months or ten weeks old, the heads still had a tendency to break. That difficulty had now been completely overcome by providing that the piles must be at least three months old, and in his opinion it was better to use ordinary Portland cement and to allow the longitudinal rods to come right up to the surface of the head. Latterly some four hundred piles had been driven at that site; they had all been over three months old, and only a slight spalling of one pile only had occurred.

The Authors had emphasized the importance of the packing. At the London University site it was found that when a pile-head showed signs of failure it was possible to complete the driving if new packing were put in, and the Authors, from their experiment on a test-pile at the site, had shown that the reason for that was that the peak-stress at the head immediately dropped from 3,000 down to 1,500 pounds per square inch. It was interesting to note that, before the set at the site in question was fixed, three test-piles were driven, the set being calculated on Hiley's formula, and in all three cases the test load was within 5 per cent. of the calculated amount before extra penetration occurred.

There were one or two points in the Paper in regard to which he would like to ask questions. Firstly, he took it that if k/A was small—for example, 10,000—then the packing was soft, and if it was, say, 40,000, the packing was hard. Turning to the example on p. 202 the assumed value of C, which was taken as 1·02, appeared to be rather high. He thought it should vary in accordance with the packing, which was hard in one case and soft in the other, and he would like the Authors to say whether he was right or wrong. He did not quite understand what the figure of 0·15 was, which had to be added to twice the set. In the example, was not k/A round the wrong way? The Authors said, "The calculation therefore shows that there is a possibility of dangerous foot-stresses with head-cushions of great stiffness," whereas he thought that the stiffness was great when k/A was 40,000. In conclusion, he would like to say that he welcomed very much anything which would give information on what was happening below the ground, and, if the head-stress indicator proved to be practical, engineers would find it to be of great value to them on the site.

Mr. McCarthy. Mr. M. J. C. McCarthy remarked that any research work which would throw light on the important subject under discussion would be welcomed not only by contractors but also by engineers and others concerned. The Concrete Piling Panel of the Institution of

Structural Engineers was also investigating pile-driving problems, chiefly by examining observations made on actual contracts. What did emerge very plainly from the Paper, in his view, was that the pre-cast pile had its limitations, and that there were cases which were most unsuitable for its use, for example, when the driving was through strata which might cause the toe-stress to exceed the safe limit. He believed that engineers would revise their ideas in the construction of jetties, wharves and so on and would try to avoid the driving of long concrete piles in cases where alternatives such as steel sheet-piling, or cylinders with short piles at the bottom, could be used. The piles which were driven at Lots Road and at the London University site were stiffened up at the head with mild-steel bands. He would not advise excessive stiffening-up of the head, because, in the absence of the peak-stress indicator, the breakdown of the head gave the engineer some indication that the danger-limit was being approached. Moreover, when the heads broke the contractor was likely to be much more careful in continuing the driving, when he had to stand the expense of re-heading the piles. Although, according to the Authors, slight eccentricity of the hammer-blow was not of great importance, it was to be hoped that contractors would not take advantage of that statement, since any eccentricity was likely to deviate the pile from the vertical, which was detrimental, and once the pile had deviated it was sometimes difficult to adjust the frame quickly. The amount of experimental error in the tests described seemed to be great, although not excessive, considering the difficulties involved. Where pre-cast piles had still to be used, the use of a water-jet would sometimes reduce the stresses set up in attempting to penetrate a compact stratum such as sand, gravel or ballast. He would suggest that further investigations into the different packings would be useful. He had never before heard of asbestos packing being used, and he hoped it would be tested in practice. The factor k/A seemed to be slightly confusing. Mr. Hiley, who was unfortunately unable to be present, had suggested that k could be expressed more clearly as $\frac{R}{c}$, where R denoted the force on the packing and c the corresponding compression. Mr. McCarthy.

On the University contract a single-acting hammer was employed, in which the cylinder delivered the blow. Steam was admitted by a valve at the top through the hollow piston-rod and lifted the cylinder; when the steam was released by exhaust to atmosphere the cylinder fell, but while the cylinder was being raised the weight was carried through the tail-rod on to the pile, thus damping down any vibration of the pile. In the case of the hammer used at the University site, there was a silencer on top of the valve which

Mr. McCarthy. probably accounted for any back-pressure experienced. The double-acting type of hammer was largely used in America, and was really a development of the Nasmyth hammer, which was first used for pile driving in 1845. It was a vertical double-acting steam-hammer totally enclosed, the reaction of the blow being taken by the casing resting on the pile-head. Such hammers were made up to six tons in weight with an energy of 10 foot-tons per blow and delivering 120 blows per minute. He thought that the investigations described in the Paper might usefully be extended further to cover the double-acting hammer.

Mr. Grove. Mr. G. C. Grove remarked that he had recently been engaged in the manufacture and driving of several thousand reinforced-concrete piles at His Majesty's naval base at Singapore. Those piles were of four sizes, 12, 14 and 16 inches square, reinforced on the Hennebique system, and 18-inch octagonal piles reinforced spirally. The piles, which ranged from 15 to 100 feet in length, were made of 1 : 2 : 4 Portland cement concrete of normal setting quality. Practically all the piles were driven into stiff strata consisting of decomposed granite or grey clay with a high proportion of grit, and no particular difficulties were encountered in driving. Owing to the somewhat heavy loads which the majority of the piles were called on to carry, a good deal of hard driving to small sets was necessary, yet about 65 per cent. of the piles showed no signs of damage to the heads. The heads of the remaining 35 per cent. were damaged, some slightly and some seriously. The injuries to at least 25 per cent. were due to the pile being driven out of plumb, to bad packing in the helmet, or to slackness of the guide-block on the back of the monkey, causing the monkey to wobble and not to deliver its blow normally to the vertical axis of the pile. The remaining 10 per cent. were damaged by excessive head-stress caused by the use of packing with too high a stiffness-constant.

Owing to the irregularity of the level of the stiff stratum, it was often difficult accurately to forecast the lengths of pile required, so that some of the piles had to be lengthened *in situ* and re-driven. The lengthening was carried out by splicing on a length of reinforcing skeleton and casting the concrete round it. Normal-setting Portland cement was generally used, and the piles were allowed to stand for 6 weeks before re-driving was commenced. It was then frequently found that during the period of rest the frictional resistance had so increased that the piles had set up and could not be driven by ordinary driving. In such cases, the Authors' peak-stress indicator would have been of considerable value, as it would have indicated when the safe working stress was being exceeded. It would be interesting to hear the Authors' suggestions regarding lateral reinforcement of the extension when piles were lengthened in that way, and what, if any, special precautions should be adopted in driving. It was noticed that the heads of the lengthened piles did not stand up to the driving nearly as well as the original pile-heads, but whether that was due to the vertical casting he did not know. Mr. Grove.

In one case it was decided to try to extract a 50-foot pile which had been driven in firm clay to a set of ½ inch per blow, but the attempt had to be abandoned after two 100-ton jacks had failed to produce any appreciable upward movement. Had the Authors been able to extract for examination any pile driven under conditions producing excessive internal stresses, and, if so, what were their observations?

In some cases during the maturing process piles were found to have developed fine hair-cracks, which became apparent after the period was completed. In tropical countries it was an advantage for all piles to be kept thoroughly wet from the time of casting to the time of driving. A number of piles in which those cracks existed were driven without apparent trouble, and in one case a pit was excavated alongside, the pile was examined, and it was seen that no extension of the cracks had occurred. It was always difficult to form a definite opinion as to the depth to which those cracks extended, and it would be of interest to know whether there was any means of determining it, even by destruction of the pile. He would like to know whether it would be reasonable to assume that, provided no damage to the head had occurred, the piles referred to had been driven satisfactorily without damage underground.

The sets to which the piles were driven were calculated from Mr. Hiley's formula, in which the factor C allowed for temporary compression in the pile; that factor was given in two columns in the Table, one for medium driving and one for hard driving; the former allowed for stresses up to 1,000 pounds per square inch, and the latter for stresses up to 2,000 pounds per square inch. In the absence of any instrument such as the stress-indicator which had been shown that evening, the actual stresses were not known; the instruments and methods described by the Authors would have been very helpful had they been available while driving those piles.

Mr. D. H. Stent stated that he would like to ask the Authors one question which might perhaps be premature, as their research might not have reached a stage to enable them fully to reply. He had been associated with several piling jobs where piles had developed transverse cracks during driving. In all those cases there had been a hard stratum of ballast near the surface, so that there was a long length of the pile laterally unsupported above ground which had Mr. Stent.

Mr. Stent. to take practically the full stress of driving through that hard stratum. In four or five specific cases the same conditions had produced the same results, namely, transverse cracks, sometimes spaced about every 2 feet down the pile in extreme cases. A curious feature was that, where such piles had been driven on, at least one case had occurred on each of those four or five jobs where the main bars had moved vertically upwards in the pile. In one case a bar kicked off one corner of the pile, and rose about 4 inches above the top of the pile into the packing until it was stopped by the top of the steel helmet. In another case the four bars rose and kicked off the head of the pile. In Table IV the Authors gave figures denoting the stage at which the first signs of failure were observed, and he would like to ask them what they considered to be the first signs. He wondered whether they referred to the transverse cracks of which he had been speaking, and, if so, whether they experienced any cases of the bars being loose when driving was continued. His own feeling about the cases of transverse cracking which he had met with was that they were not due simply to inadequate compressive resistance or impact resistance of the concrete, but rather to vibration being set up by the blow in the long unsupported length of the pile. That vibration produced negative and positive stresses which broke down the adhesion to the steel, as was shown by the rising of the bars; then, when the adhesion was lost, the tensile value of the steel was lost and the concrete cracked. He would like to hear the Authors' views on that point. Dr. Glanville had been good enough to examine one such case which had occurred some time ago, and he did not think that Dr. Glanville had then been able to reach any conclusions, but it would be of interest to know whether he had subsequently found any solution. The Authors stated that there was practically no tension in a pile during driving, but he did not see how transverse cracks could be produced if that was the case; such cracks seemed to him to indicate the existence of tension and loss of adhesion on the bars. He hoped that the Authors would explain that point.

Mr. Manning. Mr. G. P. Manning suggested that in giving such intensive study to the stresses in reinforced-concrete piles there was a possibility of overlooking the large extent to which the personal factor always entered into their making and driving. The Authors stated that, in addition to some kind of pile-driving formula or theory of pile-driving, there had to be a specification to support it. That was quite correct, but it was not the whole story; it was also necessary to have continuous expert supervision on the site. For example, fractures below ground might make very little difference to the recorded set, but the way in which the pile took the set would usually tell an experienced engineer whether anything had gone wrong. He agreed that pile-driving formulas usually held good only over quite a limited range. The Dutch rule, with a factor of 6, was probably the most generally used. It was correct, in his experience, for sets of the order of about 1 inch for ten blows, but it was certainly not correct for sets of $\frac{1}{4}$ inch or less for ten blows, and he did not think it was right for sets of about 1 inch per blow. For sets of the order of 1 inch for ten blows, with an ordinary size of pile, weight of monkey, and drop, the pile would generally take a test load of twice the designed safe load. The specification, of course, had to include some specification of the packing on the head. The following was a typical example he had met with in driving a small 10-inch square pile:— Mr. Manning.

With 4 inches of mats as packing, the set for ten blows was $\frac{1}{2}$ inch, and the safe load by any formula $2X$.

With 2 inches of mats as packing, the set for ten blows was 1 inch, and the safe load by the same formula X.

With no packing, the set for ten blows was 2 inches, and the safe load by the same formula $\frac{1}{2}X$.

That showed that formulas based on the set were quite useless without some specification of the packing.

Throughout the Paper he noticed that the term "dolly" was used for the head-packing, but surely that was a most unusual use of the term. The term "dolly" was generally applied to a baulk of timber used on top of the pile or helmet as a follower when the pile-head went below the ground. Speaking generally, a short dolly, say 10 feet in length, firmly held at the top and bottom, with good ends and pretty sound timber, absorbed about 50 per cent. of the effective blow; for example, if a pile were driving 2 inches for ten blows before the dolly was put on, the set would drop to about 1 inch for ten blows with the dolly in place. With a long dolly about 75 per cent. of the blow was usually lost; a set of 2 inches for ten blows would be reduced to about $\frac{1}{2}$ inch for ten blows.

He agreed that the bigger the hammer the better the driving. The recorded stresses in the piles were more or less what would be expected.

With regard to the tensile stresses in the pile due to elastic waves, he himself had never in practice seen any indication that there were high tensile stresses in a pile during driving. For example, piles above low water-level in a jetty would be expected to deteriorate visibly if they had been subjected to high tensile stresses, but they did not appear to do so.

Mr. Manning.

The reference in the Paper to the making of piles was again lacking in any mention of the personal factor. The Authors laid down five conditions which should be satisfied, but it was quite possible to comply with them all and yet make an unsatisfactory pile. The main point in making a pile was the workmanship, particularly at the head; the other factors were less important. His own experience was that normal-hardening cement was better than rapid-hardening cement for the making of piles. That statement agreed with what was said in the Paper, although it might seem to contradict it. He had found that the more rapid-hardening the cement was, the more careful the workmanship had to be; if, therefore, two cements showed the same mechanical properties under laboratory conditions, one being normal-hardening and one rapid-hardening, the normal-hardening would give better results with average conditions of workmanship on the site. He thought that that was the explanation of the difference.

He would like to know whether the Authors had carried out any experiments on steel piles, which of course could be driven and withdrawn repeatedly, and would also like to ask whether they could give any relation between the vertical resistance to driving and the horizontal resistance to displacement.

Mr. Williamson.

Mr. JAMES WILLIAMSON remarked that, at the very beginning of the Paper, the Authors said, "From the very limited knowledge available it was clearly impossible to estimate for any known set of conditions whether troubles would occur or not." As an engineer who had to deal fairly frequently with foundations, his own opinion was that if the conditions were known the problem was practically solved, and he thought that it was the same with piling. Difficulties arose in dealing with unknown sets of conditions, which could not be foreseen in the case of underground work.

The methods devised for ascertaining the actual stresses in the piles were most ingenious. In general, he thought that the results obtained showed that over a wide range the ordinary theory of impact applied to the transmission of momentum from the hammer to the dolly and from the dolly to the pile was applicable with almost complete exactness, and, according to the theory, that momentum could be communicated in spite of very wide variations in the packing at the head. When he had been studying the problem some time ago, he had been puzzled about that point, and had solved it to his own satisfaction by a simple experiment with a household spring-balance. He put a brick on the balance which sent the pointer round to 7 pounds or so, and then dropped a weight on to the brick. The pointer was driven farther round with a good deal of vibration, and then moved back. He then put some thick

Mr. Williamson.

packing on the brick and repeated the test, and found that he got quite as much deflection of the pointer and a great deal less vibration. The point where the ordinary impact assumptions began to differ was in regard to the time of the impact and the total distance through which it acted. The hammer, with 0·01 second for the impact, would in normal cases of driving be brought up in a distance of the order of 0·6 inch. If the total movement of the pile was as much as that, he thought that so far as movement into the ground was concerned, results as reliable as those given in the Paper could be simply calculated on the assumption that the momentum of the hammer was transmitted to the pile, and that the momentum of the pile was then expended by motion in the ground. When, however, the resistance at the point was such that the motion was only a fraction of the movement which stopped the hammer, it seemed obvious that the time in which the point was stopped would be less than the time of the impact of the hammer on the head of the pile, and that therefore the momentum of the pile would not be merely absorbed by friction. The Authors had indicated how the wave of compression travelling down the pile might be increased in value when it reached the point, and he thought that that occurred in those cases where the time of stopping the point was shorter than the time of the impact on the head. That idea might possibly be pursued further.

Considering the stresses shown in *Figs. 13* (*b*) in relation to the penetration of the pile at the time, and taking the case with penetration 17 feet and a 36-inch drop, it would be found that there was almost an even stress in the pile down to the point at which it entered the ground, and from there to the foot there was a gradual reduction of the stress, just as would be expected if the momentum were gradually absorbed by the friction in the ground of each foot of the pile; he thought that that would correspond to a fairly complete transference of momentum from the pile to the ground. The same effect was to be seen in *Fig. 14* (*a*), where down to 17 feet from the toe the stress was constant, and thereafter there was a gradual decrease owing to the friction of the ground and the resistance at the toe.

Some of the graphs in *Figs. 14* resembled what engineers sometimes did in foundations; they found that there was rock at certain points, and they drew straight lines between those points and assumed the lines to represent the surface of the rock. In the graphs under consideration the kinks were really determined by the positions in which the instruments happened to be. He would like to ask whether the Authors were quite confident that in the upper of the two curves in *Fig. 14* (*d*) the highest point, showing

Mr. Williamson.

the stress at the middle of the pile, was likely to be correct, having regard to the conditions of gradual reduction of stress shown on the lower curve. The diagrams generally showed reduction of stress in the portions of piles driven through clay or silt. In *Fig. 14* (*c*), with a penetration of 25 feet, the upper part of the penetration was through silt and mud. The resistance of that material might tend to reduce the stress for a certain distance below ground-level, whereas the diagram showed increasing stress, owing to the joining up of two points by a straight line.

*** Mr. Melville.

Mr. ALEXANDER MELVILLE remarked that the Authors' research had dealt effectively with two points which had long been sources of worry in practice—firstly, the tendency of engineers to insist on piles being driven to a depth regardless of what they had to be driven through, and, secondly, the necessity of specifying that piles should not be driven beyond a reasonable set. It would be good for all concerned if in due course, at the conclusion of the Authors' research, a simple expression of the results and the lessons derived therefrom could be made, as it would become the standard guide of good practice. Whilst the research had been on reinforced-concrete piles, the lessons to be learnt were really applicable to all piles—everyone had seen timber piles hammered for days on end till their lower ends were like shaving brushes, or steel sheet-piles driven till the ends were bent round and rose out through the bottom of the trench. The Paper gave the results of experience which should be an effective counter to the unduly-determined engineer who insisted on his piles being driven further at any price.

Mr. Walton.

Mr. G. F. WALTON observed that the Authors stated that little advantage was gained by increasing the longitudinal reinforcement beyond that required for safety in handling, and it appeared that no advantage was gained by the use of a concrete stronger than 1 : 2 : 4, but the Authors did not say what age of maturing they advocated. They spoke of normal cement at 28 days as being equal to rapid-hardening cement at 7 days. In practice in India Mr. Walton had found that 5-ton 45-foot piles made with 1 : $1\frac{3}{4}$: 4 rapid-hardening cement should not be driven into deltaic soil until 2 months after casting if damage in handling and driving were to be avoided. He had driven them in 1 month, but did not like to do so, as much greater care had to be taken, and even then the results were not satisfactory. Under Indian conditions he preferred to drive piles when they were 3 months old, which was equivalent to a longer period in England. Engineers were so accustomed to speak of concrete strengths at 28 days that they often overlooked the

*** The succeeding contributions were submitted in writing, owing to lack of time at the meeting.—SEC. INST. C.E.

advantage of an older concrete. He had found rapid-hardening cement of advantage in handling during manufacture and for the purpose of stripping off the moulds, but of little advantage in driving. Mr. Walton.

In another case of pile-driving he was of the opinion that he could not possibly have driven 17-foot 14-inch piles through gravel into 18 inches or 2 feet of soft rock had he not taken the precaution of maturing them for at least 6 months. The concrete was 1 : $1\frac{3}{4}$: $3\frac{3}{4}$. The resistance to driving was great, and each pile had to be driven for many feet with a set of about $\frac{1}{2}$ inch or less per ten blows, from a $2\frac{1}{2}$-ton hammer falling 4 feet. Eventually that drop had to be increased to as much as 8 feet to get sufficient penetration into the soft rock. Before those severe conditions were accepted as possible for pile-driving, a test pile was driven and extracted by excavation. He would like to know the Authors' view regarding the desirable time for maturing piles of 1 : $1\frac{3}{4}$: $3\frac{1}{2}$ to 1 : $1\frac{1}{2}$: 3 concrete, as he felt it was more important than was generally realized, and he would like to see the results of comparative tests on full-sized piles under difficult conditions of driving.

Mr. B. B. Haskew asked whether rubber had been tried as a packing material at the head of the pile; if so, what results had been obtained? Some of the speakers had remarked that normal Portland cement was more satisfactory than rapid-hardening cement, and he had also found that to be the case. Due to his experience at the London University site, Mr. Travers Morgan was of the opinion that it would be an advantage if the vertical reinforcing rods came right up to the top of the pile-head. Mr. Haskew's own experience led him to endorse that view, and he would suggest that the use of a special steel driving-cap fixed to the head of the pile—quite apart from the helmet—would be advantageous. Another speaker had found horizontal cracks in several piles, and the vertical reinforcing bars had protruded 4 to 5 inches above the head of the pile, which seemed to show that the bond between the concrete and steel had been lost and the concrete forced down. Mr. Haskew had not experienced the series of horizontal cracks mentioned, but he had seen the vertical reinforcing rods protruding 1 to 2 inches above the head of a pile during hard driving. He found, however, that that was caused by the concrete at the head being pulverized by the hard driving. The packing material got packed hard and was driven down past the tops of the vertical reinforcing rods; in some instances that continued until the vertical rods came in contact with the helmet and were burred over by recurring blows. Mr. Haskew.

Mr. A. E. Culley remarked that there appeared to be some uncertainties regarding the factor k/A which denoted the stiffness of the head-cushion. In view of the further investigation con- Mr. Culley.

Mr. Culley. templated it would seem desirable to control that factor, which was in reality a troublesome variable, by a more reliable method than that of endeavouring to discover a suitable packing. The Authors had stated :—" Asbestos fibre exhibited not only a reasonably low stiffness-constant at the beginning but maintained this condition almost unchanged. The suitability of this material for use under practical conditions has not yet been confirmed." Would it not be possible to simulate packing by adopting a combined hammer and cushion operating against hydraulic pressure within the hammer? Such an arrangement should afford a real constant throughout the driving of a pile. Further, with different sizes of orifice for the discharge of the hydraulic medium, or by a valve suitably calibrated to vary the outlet flow, any desired value of k/A could be obtained at will. Mr. Roland Bennett [1] had stated that it was possible to design a reinforced-concrete pile-head in such a way that it would withstand the direct blow of any suitable hammer, and that it was questionable whether a dolly was either necessary or desirable. A hammer hydraulically cushioned as suggested would, therefore, seem to be suitable for practical working. The further investigation of conditions would be rendered less difficult, and the various graphs produced could be simplified. For instance, the successive approximation of the maximum head-pressure referred to by the Authors in Appendix II could then be made with greater ease and accuracy.

Mr. Duckham. Mr. F. W. Duckham observed that a statement of the Authors' basic results in simple form was desirable for everyday application, and that there was still scope for a variety of sections and hammers. From experience during 23 years of making and driving some thousands of concrete piles with varied designs and conditions he was left with a sense of frequent contrast and contradiction. Designs had ranged from the strong spiral with over 20 pounds of steel per cubic foot to the weaker link type with only 11 pounds, and yet conditions had been the most difficult boulder-clay for the latter and free mud or ballast for the former. In some cases depth only and no set was specified, and such piles had been found to pull down a building instead of to support it, owing to settlement of new filling. In other cases, on the contrary, adequate set had been surpassed and the piles hammered to destruction. There had indeed been a decided need for a rational review of the whole subject, to ensure economical adaptation of means to the best end.

Beyond the simple relation between pile-strength and ground-resistance in homogeneous strata, there still remained that most

[1] "Pile-Driving and the Supporting Capacity of Piles," Inst. C.E. Selected Engineering Paper No. 111.

Mr. Duckham.

awkward of all conditions—isolated obstruction such as in boulder clay—where the pile-shoe was forced laterally and the pile fractured. Here it would seem that piling should not be considered as a suitable method until some means was found of giving the point a fair vertical lead by boring a preliminary, or pilot, hole, following the simple example in carpentry of using a gimlet or bradawl to introduce a screw or nail. Unfortunately the current cost per foot of percussive boring was about three times as much as the cost of the pile. It seemed, therefore, that the invention of a rotary drill that could quickly and steadily bore down to a depth of about 50 feet at a cost of the order of 1*s*. per linear foot would be most valuable.

Mr. Herrod.

Mr. HAROLD HERROD observed that several interesting cases of damage suffered by pre-cast reinforced-concrete piles during driving had been mentioned. He had had very similar experiences, particularly when using extremely slender piles. On one contract piles up to 75 feet in length and 14 inches square cross section (which, he believed, had a greater slenderness-ratio than any other piles driven in Great Britain) were driven for the foundations of tall transmission-line pylons. Continuous trouble was encountered, the pile-heads repeatedly fracturing. Driving was done by a 4-ton drop-hammer, elm packing up to about 4 inches in thickness being employed between the helmet and the pile-head. The heads of the piles appeared to be the most seriously affected parts, but in one or two cases the pile-shaft was damaged 10 or 12 feet below the head. After experiencing those troubles in the early stages of the work, and with a view to lessening them, the upper 3 feet of each pile was constructed with aluminous cement, but little apparent benefit resulted. Test-cubes made from the concrete showed reasonable results. The ground through which the piles were sunk consisted of clay at the top, then fairly soft warp, then fine sand (water-charged) overlying red clay at a considerable depth. The trouble was finally lessened by aiding the descent of the pile by water-jetting, and by giving the piles a much longer maturing period, equivalent to that used with ordinary Portland cement, although rapid-hardening cement was used throughout. His opinion at the time was that the damage to the concrete was caused not so much by longitudinal waves of vibration from head to toe, but by transverse vibrations, due to the fact that the lower portion of the pile was more firmly embedded in a tougher stratum than was the upper portion. Each pile was held back to the leaders by a number of gauge-bolts along the upper portion in the usual way, and it was thought that, owing to the slenderness of the piles, each hammer-blow tended to cause a minute instantaneous whip. As the hammer was lifted after each blow, the head would whip across and be struck by the next blow with a slight

Mr. Herrod. eccentricity, which would tend to damp out the first vibration and introduce a further one, the vibrations continuing until disintegration set in. One instance occurred of severe damage to the pile-shaft below ground. At a depth of 10 or 12 feet below the surface it was found, on excavation for the pile cap, that the upper portion of the pile had moved bodily cross the lower portion, being driven down alongside it, the main reinforcement-bars taking the form of a well-developed " S " curve. The driving chart showed no indication of the breakage.

It was shown in the Paper that under certain conditions the stress at a point at or near the foot of the pile could reach an intensity approximating to twice that at the head. It was known in many cases that the concrete at the head fractured and spalled under driving, which would arouse strong apprehension as to the condition of the pile below ground, where it was not visible. The considerations of stress-intensity in the Paper were based on equal cross-sectional areas of concrete at the various points along the pile, but it should be remembered that practically every pre-cast pile was considerably lessened in cross-sectional area immediately above the cast-iron or steel shoe, where the concrete itself was reduced in area to probably one-quarter or one-fifth of that obtaining along the normal shaft. It would therefore appear that in many instances, where it was thought that a satisfactory set had been reached and that the pile was sound, the concrete above the shoe would probably be completely disintegrated, and the pile mushroomed over the shoe. The occurrence of such damage would depend upon the relative natures of the successive strata penetrated, but it could not be a rare happening. It had to be inferred that the fact of being able to ensure a sound, well-constructed pile of pre-cast reinforced concrete which could be inspected visually before driving was not of all-embracing value, as at that stage the pile had been subjected to none of the factors which were likely to cause damage—slinging, erecting and driving. The state of the pile below ground after those operations was bound to be uncertain.

Mr. Malcomson. Mr. J. C. Malcomson stated that one of the piles at Lots Road Power Station had fractured rather badly at the head after having penetrated 30 feet below ground through 16 feet of mud and silt, 2 feet of sand and 12 feet of ballast. (The recorded driving when fracture occurred was 570 blows to the foot.) As it was imperative to reach the requisite toe level the pile was withdrawn, after some considerable difficulty, by means of a 150-ton hydraulic jack. It was found to have suffered no damage below ground, and the toe was perfect; large lumps of sand and ballast, considerably compressed, adhered to the toe and to the sides of the pile for some distance above the toe. In view of the great stresses demonstrated by the Authors, he would like to know whether the concrete in the toe of the pile received any assistance laterally from the highly-compressed strata; if so, would not that assistance automatically increase as the toe-stresses increased, thus preserving the pile from damage in driving through thick layers of ballast or similar materials? That might not be the case in driving to rock, but the conditions would then be known beforehand and could be allowed for by means of the steel bands mentioned in the Paper. Mr. Malcomson.

Mr. G. H. HODGSON noted that the Paper dealt principally with piles having gravel aggregate, and that crushed-stone aggregates were to be fully investigated in the near future. The selection of the aggregate was one of the most important problems; only too often the local aggregate was used simply for the sake of cheapness, with disastrous results. The stone used should have a high crushing strength combined with great toughness, and should have a rough fracture. Gravel, on the other hand, was brittle and had a smooth surface, the result being that the gravel simply pulled out under impact owing to its shape and lack of bond. Mr. Hodgson.

For reinforced-concrete piles to stand up to heavy driving, the following points should be observed:—

1. Ordinary Portland cement should be used, and adequate time allowed for curing.
2. A crushed-stone aggregate, as described above, should be chosen.
3. Every attention should be paid to the fixing of the steel and to the placing and curing of the concrete, especially in the early days.
4. Links not less than $\frac{5}{16}$ inch in diameter should be used.
5. Longitudinal steel should be sawn exactly to length.
6. The shuttering forming the head of the pile should be fixed at right angles to the length of the pile, and should be smooth and free from "wind." The chamfer should come to the outside edge of the main longitudinal steel.

Mr. R. N. STROYER observed that the Paper bore out by experiment and theory what had been found to be good practice through years of experience of pile-driving. From the discussion, however, it seemed to him either that the speakers had been singularly unfortunate in their pile-driving experience, or that he himself must have been particularly fortunate during his 25 years of such work. The difficulties and troubles related during the discussion reminded him of the early days of concrete piling, when piles were cast vertically and nursed down with soft packing and infinite care. One of the Mr. Stroyer.

Mr. Stroyer. speakers, mentioning a large contract, had stated that as many as 35 per cent. of the pile-heads on the contract broke during driving, and did not seem to think that was a bad proportion ; yet great care seemed to have been taken in all cases with the packing of the head, mention being made of as much as twenty-four layers of felt. Mr. Stroyer had never heard of such a quantity of packing being used ; and never employed more than two or three layers of wood, sacking or matting in his own work. Twenty-five years ago, when spending three years in Germany, he often saw piles driven without a helmet and with only a few layers of sacking between monkey and pile. In the very few cases where he had encountered broken pile-heads on contracts, the trouble could always be ascribed definitely to insufficient cement in the head, badly-adjusted packing, or use of the wrong kind of cement (assuming correct design of the head-reinforcement). In nearly all those cases the driving had been very hard, the usual load on a 14-inch pile being over 70 tons and, where soil conditions permitted, over 100 tons, the set being calculated on the Dutch formula with the usual safety factor, and in many cases with driving to refusal.

Nor should failure in the body occur through driving. In the cases where such failure had come to his notice there had always been other reasons for it, such as obstructions twisting the pile out of line, or similar causes. To continue hammering a long pile when the toe was in something closely akin to rock would appear to be asking for trouble. It was, of course, sometimes necessary to drive a pile through a thin sand or ballast layer overlying softer soil, but with suitable reinforcement and handling no trouble should be experienced. In a recent contract for a pier in the Thames the ballast layer (requiring very hard driving) was met at once and had to be penetrated to obtain a gradually hardening set in the clay below, the conditions being somewhat similar to those of the London University pile illustrated in *Fig. 8* of the Paper. The 15-inch piles, vertical and raking, were between 60 and 70 feet long and were driven with a 3-ton hammer, without any difficulty with either heads or bodies.

Referring to the Lots Road pile shown in *Fig. 8*, he would be glad if the Authors could give any information as to why the driving was continued through a 20-foot layer of ballast and sand into clay of the required bearing capacity. The Figure showed the resistance in the clay to be practically constant, and presumably sufficient. If the ballast overlay a good bearing stratum it would appear to have been sufficient to drive to the required set in the ballast. In a contract in Westminster similar conditions had obtained, and he drove his 20- to 25-foot piles into the sand, finishing with a hard set. At an adjoining site piles were driven through the sand and into the clay, in a somewhat similar fashion to that illustrated in *Fig. 8*. If the piles carried the load without settlement (and he had yet to hear of any such during his long pile-driving experience) it would be interesting to know where the advantage, if any, lay in continued driving in such a case. Mr. Stroyer.

Mr. MAURICE NACHSHEN asked the Authors if they would explain more clearly what was meant by "elastic set," for which they recommended an average value of 0·15 inch for hard driving conditions. Was that the same as the "quake" of the ground referred to in Mr. Hiley's Tables? On p. 200 they said ". . . the elastic and permanent sets may be measured at a position some distance away from the foot." Did that refer to the use of the set-recording apparatus shown in *Fig. 5*? If so, how could the elastic set at the foot be separated from the total temporary compression recorded by that apparatus, as the record included the temporary compression in the length of the pile as well as the elastic movement of the foot? Mr. Nachshen.

The value of the Paper would be greatly increased by the inclusion of a few more graphs such as *Fig. 21*, so that foot-stresses might be estimated for a variety of conditions. Some explanation of the "equivalent Young's modulus" would also be welcomed. It would add to the usefulness of *Fig. 18* if a line were added for $k/A = 40{,}000$, as that value was recommended for use in limiting conditions. It would be interesting to have k/A values for sawdust-in-sack packing, as it was so commonly used in pile-driving. He hoped that the Building Research Station would continue their investigations, particularly on full-sized piles driven under contract conditions.

Mr. JOHN ANDERSON observed that the Authors' investigations emphasized the effects of conditions of driving on the head- and toe-stresses of piles. The more extreme conditions were not generally experienced in driving, but where very small sets or minimum penetrations in hard strata were specified special consideration was necessary in the design of the pile to be used. It was apparent from the Paper that special attention should be given to the design of the head, owing to the lack of sympathetic action between the concrete and the steel for the upper three to four feet (unless the steel were brought to the upper surface, and a plate interposed between the head of the pile and the packing). The extra equivalent strength required was usually secured by means of circular hooping of the concrete core, without which the head of a pile with main longitudinal reinforcement was likely to spall under hard driving. Mr. Anderson.

With regard to the toe design, it appeared that similar behaviour might be anticipated. Usually, however, the design of the tapered point was such that the sectional area of the concrete was considerably less than the main section of the pile, and it was highly probable, when

Mr. Anderson. hard point driving was experienced, that the final set would actually be obtained with the toe bushed out and not by further penetration of the point. He would suggest, therefore, that that should be made improbable by providing a shoe of such a form that the concrete area was never less than the main section of the pile, and also that hooping should be provided for a length above the shoe necessary for development of the bond-strength of the longitudinal reinforcement, as in the case of the head.

A further valuable subject of research by the methods covered in the Paper would be the investigation of the behaviour of various types of splices used for lengthening piles with the object of subsequent extra driving. In his own experience, an apparently soundly-constructed splice had been found to have given way under hard driving so that the upper part of the pile deflected sufficiently laterally to continue easy penetration alongside the lower portion. Fortunately it had been possible to investigate by excavation round the pile, and to make good the defect. There might be considerable doubt as to what might be happening to similar lengthening-splices (for example, where a number of piles had been made too short as a result of misleading preliminary tests), in cases where the final sets were reached with the splices under water, even though the driving might give no actual evidence of a breakdown.

Mr. Pimm. Mr. GOWER B. R. PIMM observed that the Paper related to the behaviour of piles during driving to the sets which engineers had been in the habit of specifying in the belief that such sets indicated the bearing value of the piles. The worked example given, in Appendix II, to show how the impact test emerged from the inquiry, was therefore appropriate. On p. 181 the Authors pointed out that the calculations were based on a factor of safety of unity, which, it was observed, was not to be regarded as satisfactory. In the example given it was shown that, under the moderate conditions assumed, even that inadequate factor of safety was only barely realized, and with slightly more severe conditions would not be realized at the toe. The toe-stress given by the calculations was, however, the stress on the full area of the pile, and since piles almost invariably tapered to an area immediately above the shoe of about one-third to one-quarter of the full area, the stress given by the calculations had to be increased by from three to four times to give the stress on the diminished area, and, since such a stress would be far beyond the ultimate strength of the concrete, the concrete would inevitably fail. As driving to a very usual set resulted in such destructive stresses, even under the controlled conditions of the investigation, it seemed impracticable to devise methods of control for use in the field which would ensure a further substantial limitation of the stress. The result of the investigation, therefore, constituted an indictment of the practice of driving pre-cast piles to the sets derived from impact-formulas. Mr. Pimm.

Mr. CECIL PEEL observed that there seemed to be at least three distinct types of failure of reinforced-concrete piles during driving, and there appeared to be different causes of failure in each case. Firstly, there was the comparatively rare but not unknown type of failure caused by lateral buckling. It was generally due to a badly-fitting helmet or packing, a crooked pile, or bad pitching; it might occur with raking piles, and would usually occur early in driving. Secondly, there was the commonest type of failure, namely, spalling of the concrete at the extreme top of the pile. Thirdly, there was the type of failure which was due to excessive driving-stress within the body of the pile itself either at the head, at the foot or in the middle, which might occur even with a truly concentric blow. No doubt in the Authors' investigation, which was among the first of its kind, it was well and inevitable that attention should be concentrated upon the points of major importance and of the simplest character, detailed effects and modification being added subsequently. For that reason the research appeared to have dealt more particularly with the third of the types of failure above enumerated. It seemed to Mr. Peel that the second type was the commonest, and that local conditions might be the main cause. In pile-driving it was usual for helmets to be comparatively loose-fitting, and even with packing and a short wooden dolly it was probable that each blow was delivered to the pile-head with some degree of eccentricity. Now, as the Authors pointed out, the main reinforcement of a pile probably did not share in the distribution of the stresses near the head of the pile to the extent that was assumed in theory, and hence heavy stresses might be imposed upon the concrete near the edge of the pile, but they were not accounted for in the mathematical treatment given in the Paper. They might lead to a local spalling of the concrete covering the reinforcement at the head of the pile, followed by a failure by lateral buckling of the exposed links, especially if they were of the square type, which in turn would be followed by failure of the core-concrete at the head. No doubt such local side failure at the head was most likely to take place when the conditions were such as to cause excessively high main stresses as indicated in the Paper, but it was not necessarily so. That point emphasized the importance of adequate external lateral constraint at the head of the pile, as was indeed pointed out by the Authors. Such constraint might best be provided by bands of mild steel fixed round the head of the pile when casting, or by an external band or strap, 18 inches or 2 feet in depth, of mild steel bolted round the head of the Mr. Peel.

Mr. Peel. pile. That method had, he believed, been employed with success on piles driven for the foundations of transit-sheds at the Manchester Docks.

Those considerations pointed to the superiority of helical binding in reinforced-concrete piles, which was most usefully employed in circular or octagonal piles. The latter, however, had the disadvantage that, weight for weight, higher handling-stresses were induced than in square piles. Such stresses might, however, be properly allowed for in the design. Again, it was sometimes stated that, area for area, square piles had a greater periphery than circular or octagonal and so gave a greater frictional resistance when driven. That was true, but it might under certain circumstances be an actual disadvantage. Piles were usually employed for foundations in soft alluvial soils or filling, and were frequently driven through to hard and geologically older strata beneath. Such soft strata were always shrinking and settling, so that some time after driving the friction on the sides of the piles would be reversed if the piles did not settle, and would impose a downward drag on them, which, if they had been driven to a hard bottom, would add considerably to the loads they had to bear. That effect could often be very serious, and had sometimes led to actual failure of the piles. It was essential that that factor should be considered and allowed for in the design of piled foundations.

Were the stress-gauges situated upon the pile-axis? In future researches it might be useful if the Authors would investigate the stresses at different points in the cross section, especially near the head and foot where the distribution might not be uniform.

The most important factors which the Authors had neglected in the mathematical theory were, as stated, the damping effects of the external friction of the ground and the internal absorption of energy. It might be possible to extend the mathematical theory to include those factors, which would be most valuable, since no doubt they had a considerable effect both upon the distribution of stress and the calculation of bearing capacity. With regard to the latter, Mr. Hiley's researches and the formula he had devised appeared to be the most useful and reliable, since they formed a rational approach to the subject. Most of the other formulas which had been propounded were little better than rough rules applicable only to the very small range of conditions from which they had been derived. In using the Hiley formula it was best to make a separate estimate of the temporary compression factor C, using the values given by Mr. Hiley for the helmet and packing compression, the elastic compression of the pile (taking its full area into account), and the "quake of the ground." Allowance could also be made for the actual length of any dolly that was used, in estimating its elastic compression. The elastic compression of the pile was usually calculated (as by Mr. Hiley) upon the assumption that the resistance was uniform throughout the pile, thus neglecting side friction, and the effect of the latter was presumably included in the additional corrective-factor for the "quake of the ground," which had also to be added. The Authors' researches had indicated the importance of side friction, and it might be well if an improved method of calculating the total term C were employed, taking into account that factor as modifying the actual temporary elastic compression of the pile. Mr. Peel.

In using Mr. Hiley's formula Mr. Peel had always assessed the value of C in terms of the stress R/A, as a linear expression, which led to a quadratic equation in R or a linear equation in S, either of which might be solved quite readily.

A type of failure which sometimes occurred was that in which a number of transverse cracks appeared. In one case fifty-three piles were driven for a foundation, through 35 feet of gravel (which had been deposited through water), 4 feet of peat and silt, and 9 feet of virgin gravel, on to a bed of hard sandy clay. They were 55 feet long, 14 inches square, and reinforced with four $1\frac{3}{8}$-inch rods with $\frac{3}{16}$-inch links at a pitch of 10 inches for the greater part of their length. At the date of driving they were 5 or 6 years old, and when they had been made the test concrete had shown good results. They had been carefully handled. All the piles were driven successfully to a depth of about 50 feet by means of a 45-cwt. monkey falling 3 feet 6 inches or 4 feet. About half a dozen developed spalling at the head, and one only developed fine transverse cracks after the pile had been driven about 10 ft. and all within the space of a few blows. It was found that these cracks were situated at every link, and extended right round the pile. He had been considerably puzzled as to the real cause of that failure; perhaps the Authors could indicate it, in the light of their researches. Another of those piles, after being driven to a depth of about 42 feet, developed bad spalling at the top. It was reheaded with aluminous cement concrete and redriven after an interval of 64 hours. The driving resistance (calculated by Hiley's formula), which had gradually increased to about 68 tons up to the point of the failure, was found to be about 83 tons when driving was recommenced. The final resistance was about 117 tons after a further penetration of 7 feet. That, and many other similar cases which other engineers could, no doubt, cite, showed that the ultimate useful bearing capacity of a pile might be considerably greater than that calculated from the final set, if that set were measured in the usual way at the end of a normally rapid drive, or, on the other hand, might be considerably

Mr. Peel. less if the ground around the piles settled or shrunk, thus reversing frictional force. A useful measure of the increase of side friction could be obtained by taking a second set some days after the pile had been fully driven, and calculating the driving resistance for both sets.

Any additional knowledge of the behaviour of piles and of the factors which govern pile-driving would enable piles to be loaded safely, using a much smaller factor of safety than was sometimes adopted. That factor was sometimes made unnecessarily high—merely because it was a "factor of ignorance." It might well be that in driving either timber or steel piles the distribution of stress across a section was more uniform than in reinforced-concrete ones. It was therefore possible that further research by the methods developed by the Authors, and employing those types of pile, might yield results which would provide a closer and therefore more valuable check upon the deductions of mathematical theory, facilitating the development of the latter with regard to reinforced-concrete piles in future researches.

Dr. Glanville. Dr. W. H. GLANVILLE, in a preliminary oral reply, thanked the Members very much on behalf of himself and his co-authors for the way in which they had received the Paper, and said that it had been a great pleasure to present it.

Sir Henry Japp's examples were obtained at the beginning of the investigation, and had been largely responsible for its inception. He had not seen all the examples before, and had not fully realized how bad the conditions had been.

He had been very interested to hear Mr. Travers Morgan's experience with piles aged for three months. The increase in crushing strength between the ages of, say, one month and three months was very low for concrete as normally produced; it might be of the order of 15 to 20 per cent., or perhaps a little more, and it was notable that that little increase in strength was sufficient to prevent the piles from failing; unless impact-strength increased at a greater rate than crushing-strength, it appeared to confirm the statement made in the Paper that under certain conditions the margin of safety was small. It was also interesting to hear that rods brought to the surface at the head of the pile had produced better results. The examples given at the end of Appendix II were intended to indicate the method of using the charts, and the Hiley formula had been selected purely arbitrarily; any formula might have been chosen. The constant C as given by Mr. Hiley might be assumed to vary with the degree of compaction of the packing, but it had been kept constant in the present case because it was assumed that the same packing was used throughout, the value of 10,000 for k/A being used at the beginning of the test, and that of 40,000 after the packing had hardened up. That point did not affect the working of the example, but only the numerical results. Dr. Glanville.

In reply to Mr. Morgan's question as to whether k/A was round the wrong way in the example given on pp. 201 and 202, k/A was correctly stated, for the following reason: The sets of 0·52 inch and 0·25 inch represented the values required to produce a toe-stress of 3,000 pounds per square inch; values greater than those would produce lower stresses, and the greater the margin the better the conditions of driving. Thus a set of 1·15 inch for a soft packing (k/A 10,000) when the set to produce 3,000 pounds per square inch was 0·52 inch represented more favourable conditions than a set of 0·27 inch for a hard packing (k/A 40,000) when the set to produce 3,000 pounds per square inch was 0·25 inch. The figure of 0·15 inch referred to by Mr. Morgan was what the Authors had termed the elastic set, namely, the elastic movement and not the permanent movement at the toe of the pile.

Mr. McCarthy had referred to full-scale tests which were being carried out, and the Authors felt that a considerable amount of useful information could be obtained by getting very simple measurements from jobs. If records of elastic and plastic sets were obtained, coupled with known conditions of hammers and other factors of importance, the Authors might thence be able to forecast more accurately than they had done in the Paper the stresses likely to occur under typical driving conditions.

To regard head-failure as an indicator of what was happening under the ground was, he thought, wrong, because, as the Authors had shown, the stresses below the ground might be higher than those at the head. It seemed to him, therefore, that it was not necessarily bad to use head-bands and to try to protect the head as much as possible, particularly as to obtain any reasonable values from a bearing-capacity formula the stiffness at the head of the pile, which was determined by the packing used and the amount of destruction that had occurred there, was likely to affect the actual observed sets very much indeed.

With regard to eccentricity of blow, the Paper referred principally to transverse vibrations which would be set up at right angles to the axis of the pile if it were hit eccentrically, and which might induce tensile bending stresses. Increased compressive stress due to eccentricity of blow was another matter, and he was in complete agreement with Mr. McCarthy that every effort should be made to control the driving conditions so that eccentricity of blow was avoided as far as possible.

Mr. Hiley's suggestion of using the factor R/c instead of k was, of

Dr. Glanville. course, just another way of looking at the question. It might be simpler as a first approach to the subject, but he himself had become so intimate with the subject that it was more difficult for him to see it in the way suggested. In any case the expression R/c was only equal to k/A for materials having a linear stress-strain relation.

It would be extremely interesting to continue the investigation to cover the use of a double-acting hammer. He did not quite know what that would involve, but he thought that useful work could be done.

Mr. Grove's experiences at Singapore were very interesting indeed. The Authors had had no experience of the extraction of piles in which excessive stresses had been measured, but numerous examples of failures in which measurements had not been taken were available, and were in fact the main reason for undertaking the investigation. He knew of one pile at least which had been driven under hard conditions and where extraction showed that there was no damage to the pile, but there was no record of the actual stresses.

The Authors. The AUTHORS, in completing their reply, stated that in order to avoid repetition they would deal firstly with the manufacture of piles; secondly, with their driving; and, thirdly, with the theoretical questions raised.

All speakers who had discussed the relative merits of cements had agreed in preferring normal to rapid-hardening Portland cement. No decided superiority of one over the other had been found in the tests made at the Building Research Station, but, as suggested by Mr. Manning, the reason might be that greater care was necessary in the manufacture of rapid-hardening cement concrete. The advantages of extended curing had also been stressed by a number of speakers, that point having been dealt with by Dr. Glanville in his oral reply. Mr. Walton had inquired what maturing period was considered suitable for $1 : 1\frac{3}{4} : 3\frac{1}{2}$ to $1 : 1\frac{1}{2} : 3$ concrete made with rapid-hardening Portland cement. The results obtained at the Building Research Station indicated a continuous increase of impact-strength with age, and the maturing period should be the maximum possible. Only a relatively small increase in strength, however, could be expected after 28 days.

The Authors were in agreement with Mr. Manning and others regarding the importance of good workmanship in the construction and casting of the piles. They were interested to know from Mr. Peel that the method of safeguarding the head of a pile by external bands had been successfully used at Manchester.

Mr. Haskew had inquired whether rubber had been employed as a packing material. Tests at the Building Research Station had shown that under suitable conditions rubber was highly satisfactory.

Its stiffness was low, and remained constant over many thousands of blows. One of the difficulties of employing rubber under present conditions was due to the considerable lateral expansion which had to be allowed to take place, and which made its use in ordinary helmets impossible. The Authors.

A hydraulic cushion incorporated in the hammer had been suggested by Mr. Culley. Some form of mechanical cushion was undoubtedly an urgent requirement. The problem had received some attention at the Building Research Station, with the object, however, of producing a mechanical cushion to be fixed to the pile rather than to the hammer. The objection to incorporating it in the hammer was that the impact of the piston itself on the bare pile-head would induce high stresses of very short duration, and packing would therefore still have to be used. That objection did not apply to hydraulic devices placed on the head of the pile.

Several speakers had mentioned the importance of local stress-concentration due to uneven distribution of packing material at the head of the pile. That had been emphasized in the Paper (p. 174). Mr. Stroyer's remarks on the use of twenty-four felts in driving piles appeared to have been made under a misapprehension. Thicknesses of twelve and twenty-four felts were used for test blows to obtain data relating to packing materials with widely differing values of k/A. Apart from those tests, the piles were driven with the packing normally used by the contractor and described in the Paper.

With regard to the toe of the pile, it had been suggested that the reduced area of concrete at the toe was bound to give rise to greatly increased stresses. That assumed the resistance to driving to be concentrated at the extreme point of the pile, whereas in practice it was certain, unless an obstruction was encountered, that the load was distributed over the inclined faces of the concrete forming the toe of the pile, and that the full load was not sustained by the reduced section. Mr. Malcomson stated that a pile extracted at Lots Road after penetration of the ballast was undamaged, although the toe-stresses were undoubtedly nearly as high as those at the head. Under such driving conditions it was, nevertheless, very desirable that measures should be taken to strengthen the lower part of the pile, by increasing the amount of transverse reinforcement and by external banding.

Mr. Stroyer asked why driving was continued through the layer of ballast at Lots Road. The Authors were concerned only with the calculation and measurement of stresses ; that was therefore a question with which they were not concerned and which was decided by the engineer responsible for the structure.

Perhaps the most interesting, though also the rarest, type of

The Authors. failure mentioned by the speakers was that by transverse cracking, examples of which had been given by Mr. Stent and Mr. Peel. The driving conditions under which the cracks were developed appeared to be well-defined, and were those of hard driving against a relatively impenetrable medium close to the surface of the ground, so that the major part of the pile was above ground and was unsupported. The appearance of the cracks definitely proved the occurrence of tensile stresses, but it did not appear possible, at the present moment, to show conclusively how the tensile stresses originated. The first possibility was that the conditions might be those represented by the stress-time curves of *Fig. 9*, in which a 15-foot pile driven against a hard base and undamped by skin-friction vibrated longitudinally at its own natural frequency, giving rise to alternating tensile and compressive stresses in the middle part of the pile. Damping of the vibrations was probably reduced to a minimum, owing to the hammer rebounding from the head and the pile from the ground, thus leaving the pile free at both ends, the optimum condition for the maintenance of vibrations. The rarity of such failures was an argument against that explanation, and pointed rather to some chance combination of unfavourable conditions. Also, Messrs. Stent and Peel, in their description of those failures, had implied that the cracks occurred over the whole length of the pile, and not only towards the middle as would be expected on the basis of the above explanation.

An alternative explanation was that the cracks might be due to excessive transverse vibration. It had been stated in the Paper that the tensile stresses due to transverse vibrations produced by a single impact on a sound pile were found mathematically to be insufficient to cause failure, but that it was possible for the vibration to be augmented by resonance. The driving conditions were such as to minimize damping of transverse as well as longitudinal vibrations. If the interval between the blows of the hammer were a small multiple of the period of transverse vibration of the pile, the amplitude of the vibrations might be sufficiently augmented by slight resonance to cause tension failure. The required combination of conditions to produce that state of affairs was likely to recur rarely. If the second explanation were correct the preventive measures would be (1) to ensure that the blow was struck axially and that the helmet and dolly fitted evenly on the pile-head, and (2) to restrain the pile at several points along its length and prevent swaying of the frame. If the first explanation were adopted the only cure would be to use thicker packing and/or a heavier hammer.

Mr. Stent asked whether transverse cracks were taken as the first sign of failure in tests to destruction. The transverse cracks produced were always extremely fine, and were not considered sufficient

The Authors.

to endanger the safety of the pile ; the first signs of failure recorded in the Tables were those of failure in compression. It might be noted, in passing, that experiments had shown that generally fine cracks were gradually healed by further hydration of the cement, and in such cases did not lead to progressive deterioration of the pile.

Mr. Stent stated that several cases of vertical movement of the longitudinal reinforcement had occurred in conjunction with transverse cracking. As he suggested, the vertical movement certainly indicated bond failure. It was possible to explain the upward movement of the bars by supposing that the cracks were first opened symmetrically by transverse vibration and were then closed under the compressive impact-stress by the concrete above the crack slipping down the bars. Of greater importance than the actual movement of the bars was the state of affairs indicated below ground. It was difficult to explain how a protruding bar had been forced upwards unless failure had taken place below ground-level.

Points of theoretical interest had been raised by various speakers, some of which had been dealt with in the preliminary oral reply. In answer to Mr. Nachshen, the value of 0·15 inch for the elastic set was the same as the " quake " of the ground at the toe of the pile. When the elastic set was measured elsewhere in the pile a correction had to be made for the compression of the pile. For driving against a hard stratum that was done by subtracting from the measured elastic set 0·004 inch multiplied by the length of pile in feet below the point at which measurement was made (see p. 201, Appendix II). The equivalent Young's modulus E, the mathematical expression for which was given on p. 192 (Appendix I), together with the average density ρ, determined the velocity $\sqrt{\frac{E}{\rho}}$ with which the stress-disturbance travelled along the pile. Mr. Nachshen had also inquired whether the k/A value of sawdust was known. That material had not yet been included in the series of tests now in progress, but experience with test-piles had shown that when first used it had a low stiffness and that it was compacted during driving until ultimately its stiffness approximated to that of a block of wood.

Mr. Williamson had endeavoured to show that the results obtained might be explained without recourse to the elastic-wave theory. In his interpretation of the curves of *Figs. 13* and *14* he implied that the stress in the upper portion of the pile remained uniform as far as the point of entry into the ground. That happened to be approximately correct in the Figures shown, although it had to be remembered that the maximum values did not occur simultaneously. For easy driving the point at which the stress began to decrease sharply was, however, not necessarily that at which the pile entered the ground, The Authors. but depended very largely on the shape of the stress-wave from the head, and thus on the packing and the weight of the hammer. All points at which the stress-wave from the foot arrived before the maximum had been attained would show reduced maximum stress. Interpretation of the records on the basis of the static theory was therefore likely to be misleading. The point raised as to the value of the stress at the middle of the pile in *Fig. 14* (*d*) had been dealt with in the Paper (p. 169).

The Authors were in agreement with Mr. Peel that it would be most valuable to investigate the variation of stress in a cross section of a pile, particularly at the head, but the problem presented considerable experimental difficulties. In the experiments described the gauges were all situated on the axis of the pile, except in two piles in which additional gauges were cast eccentrically in an endeavour to detect transverse vibrations (see p. 177).

In reply to Mr. Manning, the Authors were unable to give any relation between the vertical resistance to driving and the horizontal resistance to displacement. No experiments had been carried out with steel piles.