

Discussion.

The Authors introduced the Paper with the aid of a series of lantern-slides and wire models.

Mr. Hammond observed that the design of earthquake-resisting structures had been studied seriously for many years and a reference to it had been introduced into the Paper in order to show the similarity between earthquake vibrations and vibrations resulting from mechanical sources. The earthquake zones of the world were very widely distributed and many of them occurred in highly industrialized and fairly thickly populated districts. As a general rule, they followed the geologically newer mountains of the world. It was an interesting fact that when the first atomic bomb was tested at Los Alamos, in New Mexico, seismologists had had an opportunity, for the first time in history, of taking some very remarkable records of ground movements, because there a known high energy impulse took place.

The Authors considered that the following words of Professor L. S. Jacobsen, who for many years had done a great deal of work in America on earthquake-resisting structures, were particularly appropriate :

“ It is true that at present very few engineers can afford to make searching studies of the dynamic properties of the structures they design. Time limitations demand that so-called ‘ rules of thumb ’ must be used for assuming the magnitudes of dynamic loads. Because of this insufficient and imperfect knowledge of ground motions that occur during earthquakes, it is obvious that designers are not justified in making any specific assumptions in regard to the periods, durations and intensities of the composite motions.”

Mr. Jacobsen had stated that measurements had to be taken with instruments first, and had added :

“ Whatever their attitudes are toward the ground-motion question, they are forced to admit that forward and backward as well as up and down motions occur. This fact alone means that dynamic loadings varying with time must be sustained by the structures. . . . How is sound engineering judgement concerning seismic loadings to be formed ? Naturally one must admit that actual field evidence has given and still gives the first and indisputable clue as to what ‘ stands up ’ and what ‘ falls down ’ or what is seriously damaged. Under no circumstances can one afford to minimise the value of the expensive lessons given by ‘ Nature’s own laboratory ’.”

A number of attempts had been made in Great Britain and in other countries to isolate buildings from ground vibrations by erecting them on cork, asbestos, and other materials, but the Authors had not yet found a single satisfactory result. None of the materials tried seemed to be of

much use. Nevertheless, the Authors felt that success could be achieved and they would like to learn of other cases in which attempts had been made in that connexion.

Mr. H. C. Husband observed that he had no personal experience of measures to reduce the effect of earthquakes, but a very interesting description had been published in December 1946, in *Civil Engineering* (New York), of a new three-storey building in Los Angeles, in which sixty-five stanchions, each carrying a vertical load of 120 tons, were carried on sixty-five double roller bearings, giving them complete freedom in the horizontal plane. The external horizontal anchorage to the whole of that quite large building was coupled up to a stiffer structure at one side.

Ground vibrations from mechanical hammers had been dealt with in a rather interesting way in Sheffield for about one hundred years, by means of trenches dug round the affected zone and filled with horse-dung. The problem was not quite so difficult at Sheffield as elsewhere, because broken shale or sand-stone was quickly reached, and if the surface strata could be isolated a considerable measure of success was achieved. With the exception of mechanical hammers, the most generally troublesome machine was the large reciprocating air compressor. Even the best known makers of those large compressors did not supply balanced crankshafts unless they were specified by the purchaser, and then there was a considerable increase in the cost. Vertical air-compressors of capacities ranging from 500 to 6,500 cubic feet per minute were usually two-cylinder machines with their cranks either opposite or at 90 degrees, and in neither case was it possible to achieve a very high degree of dynamical balance, but in all instances where those machines had to be used it was a very good thing to consider the ground vibration in connexion with the crankshaft design. Different compressors might propagate ground vibrations in different directions, and the same method of reducing ground vibration or protecting adjacent structures would not be the best in every instance. The difference between the external forces set up by compressors with cranks at 90 degrees and 180 degrees were very striking indeed.

Again, the users of large compressors were usually guided by the makers' foundation drawings, which showed, as a rule, the minimum size of concrete block, and that was put in without any very careful consideration of the actual nature of the ground—although the compressor makers usually gave a warning to that effect. In the larger sizes of compressor, the compressor and the driving motor were rarely on the same bedplate, and reliance was placed upon the concrete foundation block to maintain the alignment between them. That added considerably to the difficulty and cost of mounting the combined machine on a base suspended by a system of coil or leaf springs, although that method of reducing the transmission of vibration had the advantage of being capable of analytical design. Another very serious practical disadvantage of spring suspension was the necessity of providing flexible connexions for air and water pipes.

In the cases of two 5,000-cubic-feet-per minute compressors, each driven by a 1,225 horsepower synchronous motor at 210 revolutions per minute and delivering air at a pressure of 150 lb. per square inch, the ground was a moderately firm clay which had been tested by Mr. Crockett with a vibrograph and an artificial disturbance produced by hammering the ground with the bucket of a mechanical excavator. Foundation blocks of greater mass than those normally recommended by the compressor manufacturers were adopted, cast inside sheet-steel piling and surrounded by tightly packed sand between the concrete and the clay after the piles had been withdrawn. Mr. Husband was not convinced by the Author's suggestion that the use of sand packing served little useful purpose, particularly where, as in the cases concerned the clay had properties different from those of the sand. The axes of the crankshafts had been arranged at right angles, which was advantageous when the beats of the two compressors synchronized and they were running at almost exactly the same speed. The installation was in a closely built-up area, and special efforts were made to eliminate air-borne vibrations, which sometimes disguised the ground vibrations. The engine-house in question had been very heavily built in brick and reinforced concrete, with a good deal of lateral stability, which had proved very successful in keeping any disturbance within the building.

In another installation, under construction, to house five compressors having a total capacity of 12,000 cubic feet per minute, the new house and combined foundation replaced an existing adjacent installation. On account of site restrictions, both buildings were within 100 yards of a large cinema building, to which serious vibrations had been transmitted from a two-cylinder vertical compressor of 2,500 cubic feet capacity, running at 333 revolutions per minute with opposite cranks. When that compressor was first installed, about twelve months ago, bolted directly to a concrete foundation block, the balcony of the cinema was stated to vibrate so seriously as to cause the audience to leave. The motor and compressor were then mounted on a heavy structural steel frame supported on spring pads. Alarming vibration took place as soon as the compressor was started up on that spring base, and the compressor would certainly have been seriously damaged if it had been allowed to run. It was then decided that the first thing to tackle was the compressor, the makers of which were asked to redesign the crankshaft and to provide the best possible balancing. The compressor was then put back on to the spring frame, and the spring suspension adequately isolated the remaining vibration. No trouble had since been experienced.

A new design for carrying five fairly large compressors, of about 400 horse-power each, was rather at variance with the principle illustrated in *Fig. 46*. Mr. Husband had been obliged to limit the amplitude of the machinery vibration and, instead of having comparatively deep cork or spring pads, reliance was being placed upon the large combined mass of

the inner and outer parts of the foundation, coupled with the restraining action of the bulb piles and the ground surrounding them, to prevent vertical vibrations of any appreciable magnitude. Each compressor was on its own heavy block, there being five compressor-blocks in a strong reinforced-concrete tank about 100 feet long, which, in turn, was anchored to a system of heavy bulb piles driven into mixed clay and sand strata. It was expected vibrations would occur more in a horizontal direction, principally normal to the crankshafts, and those were intended to be damped out by the vertical layers of cork between the individual blocks. The blocks would be cast tightly up between vertical layers of cork, the layers of cork being parallel to the crankshaft axes. The layers of cork would also serve the useful practical purpose of subdividing what would otherwise be a dangerously long foundation block to cast in one piece without risk of cracking through some of the numerous holding down bolt holes.

Mr. Husband wished to endorse the Authors' recommendation that a thorough geological investigation and vibration survey should be undertaken before advice was given on vibration problems. Engineers who did not insist upon using the available means of determining the character of the local conditions before giving advice placed themselves on the same level as water-diviners.

He was opposed to incurring high expense structurally whenever there was a possibility of reducing the source of vibration to reasonable limits, and he considered that in many cases closer co-operation was desirable between the structural engineer and his mechanical colleagues. There could be no doubt that people both inside and outside industry were becoming more vibration-conscious, and he was sure that in most cases systematic investigation would indicate a method of eliminating the trouble.

Engineers owed much to the research work carried out by Mr. Crockett and his colleagues in the Department of the Chief Scientific Adviser.

Dr. A. O. Rankine observed that, as a geophysicist, occupied in finding oil, he was interested in making the earth vibrate as much as possible, instead of wishing to stop such vibration; but there was a good deal of similarity in the background of those two subjects. He and his colleagues created artificial earthquakes in the course of their work; they might explode as much as 3 tons of gelignite in a hole and observe how the surface of the earth moved perhaps 14 to 15 miles away, because they had learned through experience that such observations, carried out systematically, enabled them to discover a good deal about the deep underground structure of the earth reached by some of the vibrations referred to by the Authors, which penetrated the earth and went down to the harder strata below. The seismograph, the instrument by which they hoped to measure how the earth was moving (it was much more sensitive than the vibrograph, because it was used at much greater distances away), might be compared with the house in the case described by the Authors. The seismograph

consisted of a heavy mass which the geophysicists did not wish to move at all when the earth moved, just as the Authors did not wish their house to move when the earth moved. The geophysicists also used springs to ensure that the seismograph would not move when the earth moved, and the principle which they adopted was the same as that which the Authors had indicated. In order to obtain a true record of how the earth was moving—which would be obtained only if the heavy mass in the seismograph did not move when the earth moved—they arranged that its natural frequency should be very low in comparison with any of the frequencies which it was likely to encounter in the motion of the earth. If the Authors attached an indicating device between the earth and their house, so that they would be able to see how the earth was moving with respect to the house, they would have a very large-scale seismograph of the same kind as Dr. Rankine and his colleagues used on a smaller scale.

He could confirm that, as the Authors had indicated, the motion of the earth was very complicated, even when the original source of the vibration was comparatively simple; it became more and more complicated with distance, for the reasons which had been indicated.

With regard to the persistence of the so-called natural vibration of the particular kind of soil, was it that particular vibration which was the danger, or were other frequencies which were transmitted from other sources, such as machinery, really the cause of the trouble? To put it quite concretely, was it possible that the mere dropping of an unexploded bomb in the neighbourhood of a building could give rise to a sufficiently prolonged earth vibration to cause resonant damage in the building, or had the stimulus to persist for a much longer time before damage could occur?

Mr. W. A. W. Lankshear observed that for some years he had been actively concerned with attempts to stop the transmission of vibration by the use, in particular, of cork. He entirely agreed that stopping vibration at its source was preferable to indulging in an expensive cure once the vibration had been propagated. But since it was not always possible to stop the vibration at source, an attempt had to be made to track down the vibration and to limit it to a certain sphere of influence where it would do least harm.

He believed that not enough was known about the general properties of cork. The cork in question was not the material used for the stoppers of bottles. It was a product of the natural wood, which had been granulated, put into a mould, and baked. It was, in fact, a homogeneous granular material of a woody cellular nature—a wood bark which, through the baking process, had lost much of its volatile oil, and had become a homogeneous cellular mass.

In the past, unfortunately, comparatively little had been known about the true properties of that material or its correct application, and he welcomed the work which had been done by the Authors in that respect, because it formed a very real step towards a technical—but not too

technical—appreciation of the problems which confronted anybody who had to isolate vibration.

Formerly cork had been used on the basis of the spring formula. The natural frequency of the spring varied with its various characteristics and the method of loading, and the three main properties of cork had been regarded as analogous to those of the spring. The density of the cork, from which most of its mechanical properties were derived, was analogous to the stiffness of the spring, whilst the loading of the spring and the loading of the cork were a direct parallel. It had been found that the natural frequency of cork varied with the loading and was almost directly proportional to the density; and the range of density of normal cork, which was from about 7 lb. per cubic foot to about 22 lb. per cubic foot, should allow one to cope with any frequency within the normal structural ranges. By that he meant that it should be possible to stress the cork or other vibration-pad to the point at which its frequency would be sufficiently far removed from the natural frequency of the source of vibration to prevent it transmitting any considerable amplitude from the vibration.

The compression of cork varied, very roughly, in relation to its density. At the lower end of the scale, 25 per cent. compression could be obtained with a load of about 30 lb. per square inch, whilst at the upper end 25 per cent. compression could be obtained with about 120 lb. or 130 lb. per square inch.

In the past cork had been used in various ways in respect to vibration insulation. It had been put under stanchions and under the feet of small machines and motors; had been used as a lining for concrete bases cast in situ in pits, and had even been used as a break in the invert of a tube.

Mr. Lankshear had been asked to investigate the use of cork as a suitable medium for casting concrete or for being placed in a position where it would have to stand the test of time, and he had studied the problem from the point of view of rot. He had concluded that nothing except the white ant, which could get into almost any type of cellular material, would affect the cork once it had been baked and formed into a homogeneous slab.

Thousands of years of the use of cork had provided extraordinary evidence of its durability. It had been taken out of an Egyptian tomb which had been sealed for centuries, and had been found to be still quite usable. He believed that the Romans had used cork a good deal; and certainly the Spanish peasants, in the districts where it was grown, had used it for many years for rough forms of insulation.

The cork industry, which had devoted a great deal of time to the study of the material from the point of view of insulation, had been hampered in its work by a lack of precise knowledge about the behaviour of materials with regard to the transmission of vibration. The normal static Young's modulus of cork was known, but very little was known about the dynamic Young's modulus. More exact knowledge of vibration problems was required, and there was also a need for some means whereby the consulting

engineer could have access to information which was not too academic but which he could use and apply with certainty to his problems.

Mr. R. B. Grey observed that his experience during the past 35 years had been concerned mainly with vibration and noise caused by machinery and the effects of explosions on property in blasting operations.

With regard to noise and high-frequency vibration, he had once been asked by the husband of a very popular singer whether it would be possible to prevent her voice being heard all over the house—a problem which could have been partially solved by the application of the principle shown in *Fig. 47*.

The Authors had mentioned the collapse of a house at a considerable distance from a large forging hammer. Had any vibrograph records been taken around the hammer and in the house before its collapse? If so, what amplitudes, frequencies, and accelerations were involved, and what was the distance between the hammer and the house?

He considered that whether a structure should be founded on rock, or not, would depend upon the circumstances. In a recent investigation of damage caused by blasting operations, the vibrogram of which was similar to that of a hammer, a well-built stone cottage resting on lime-stone had been found to be seriously damaged by the explosions in an adjoining quarry, whilst other cottages, about twice the distance away, built upon overburden about 6 feet deep, had been practically undamaged. That suggested that, if a building was on rock and had to be protected from vibration from a hammer, the hammer should be on the overburden of soil, and vice versa, the soil acting as a resilient layer.

With regard to trenching around a vibrating machine, such as a Diesel engine, Mr. Grey's experience had been that if the out-of-balance forces were vertical trenching was of no value, but that if they were horizontal a reduction of nearly 50 per cent. could be obtained by trenching. The foundations concerned had been about 10 feet deep, in a clay soil.

In connexion with the machine foundation shown in *Fig. 46* embodying four spring pads of cork, each of which took a static load of about 12 tons had any provision been made for the replacement of the cork? He had found that a loading in excess of 12 lb. per square inch, or about three-quarters of a ton per square foot, on natural cork, tended to cause gradual settlement. He knew of one foundation which had settled about a $\frac{1}{2}$ inch in 30 years. He believed that the National Physical Laboratory's acoustical laboratories were mounted upon natural cork about 12 inches thick, but that provision was made for refitting after settlement. He also knew several buildings in London where the stanchions had been isolated, some on cork and some on other types of material, but he believed that that affected only the higher or audible frequencies.

Although helical or laminated springs were specially used for isolating foundations, he had obtained very good results from the application of cork to properly designed machinery foundations. He had mounted a

number of power hammers and drop stamps upon spring-isolated foundations with about 85 per cent. reduction in amplitude and upon cork with about 50 per cent. reduction in amplitude of transmitted vibration. He would be interested to know the percentage reduction of amplitude obtained by means of the compressed air springs and hydraulic damping, and what mass of concrete was used relative to the kinetic energy of the hammer. He presumed that the Authors referred to a hammer or drop stamp foundation. He would also like to know whether the compressed-air spring system could be applied to a foundation for a regularly running Diesel engine, and, if so, how the natural frequency of the compressed-air spring could be calculated so as to avoid resonance.

Mr. W. C. Andrews observed that the Paper described a continuation and development of work on the behaviour of hammers and their foundations which Mr. Crockett and he had carried out, and therefore he was pleased to note the considerable extension, both in content and in usefulness, which the Authors had made to the knowledge of ground vibrations.

He wished to emphasize or underline some of the Authors' statements. Firstly, it was important, in the use of cork or any similar form of spring, to subject it to optimum loading. A common mistake was to use too much insulating material. He wished to draw attention to the value of asbestos, especially when reinforced, to prevent lateral movement, and also to the poor properties of sand, particularly when it was wet. Considerable similarity existed between the principles enunciated in the Paper and those of acoustics, and a study of the forms of construction which had been developed in connexion with acoustical work would be found useful by persons interested in the subject of ground vibrations, particularly in relation to sandwich constructions as opposed to mass.

Whilst Mr. Andrews appreciated the value of cork he wished to utter a word of warning. It was not easy to obtain a uniform material, and it had to be kept dry, as its value was lost when it became wet. When used as pads for machinery foundations cork could be kept dry fairly easily, but building foundations were buried and considerable cost was involved in keeping the cork dry.

He agreed with the Authors that insulation at joints in frames was of little value. He considered that more successful results were likely to be obtained with rigid or portal frames, the framework being treated as a whole and not in individual parts.

The Authors had criticized the construction of the Grand Central Station in New York, but could they state in exactly what respect the construction had failed? Detailed information, including the load intensity, would be useful, as the form of construction described had been extensively used.

Mr. W. A. Allen observed that the insulation of ground vibrations by resilient foundations seemed clearly to be the only solution of the problem which had a general application in building design, because it was the only solution which offered any reasonable degree of immunity from the noise

nuisance to which the vibrations often gave rise. The resonances in individual floor and wall panels were troublesome, because the natural frequencies were in the audible range and, moreover, were in that part of the range where the difference between the threshold of hearing and the threshold of pain was very small, so that sounds which were audible were frequently very uncomfortable; therefore, measures of insulation of the type proposed were likely to find a much wider application than the Authors had suggested.

Several references had been made in the Paper to steel springs and cork as suitable resilient materials for foundations. The manner of using the cork which the Authors described was obviously a considerable improvement on the usual methods, but had it been found to reduce the tendency of the material to plastic flow? Several cases had been reported to the Building Research Station in which the thickness of slab cork had permanently decreased by 30 or 40 per cent., and even more, under design loads, with extremely embarrassing results, and at first sight, no reason was apparent why the arrangement described by the Authors should not give rise to similar inconvenience.

In the acoustical laboratories of the National Physical Laboratory, to which Mr. Grey had referred, the thickness of the cork had been 3 inches, and it had been banded with 2-inch metal strips to enclose it. Ultimately it had been removed because the cork had flowed to the point where the structure was resting upon the steel and the insulation had therefore diminished to nearly zero.

The only mention made in the Paper to rubber was a brief reference to its use under compression, where it was certainly at a disadvantage. Rubber-in-shear mountings operated effectively in many difficult circumstances. The Authors had mentioned the risk of deterioration, but, when some thought had been devoted to that problem a few years ago in connexion with acoustics work at the Building Research Station, it had seemed feasible to design a mounting in which the units would be replaceable.

The Building Research Station hoped to begin the construction of an experimental block of flats in 1947, for the purpose of demonstrating and studying sound insulation techniques. The treatments all involved the introduction of comprehensive structural discontinuities, and, after studying the Paper, those concerned with the work were considering the extension of the proposed measurements to examine the effect of ground vibrations transmitted into the structure. Mr. Allen anticipated that a considerable reduction of resonance effects would be found, but that remained to be seen.

In any general discussion of the design problems of resilient foundations consideration should be given to their effect upon the relationship of the structure to the footings. For instance, when a resilient was interposed the effect of non-uniform settlement of the footings would presumably be less noticeable in the structure, owing to the relative stiffness possible in the

frame. If so, that would seem to have attractive secondary effects in reducing cracking, which would be appreciated by those concerned with the design and maintenance of buildings.

Mr. G. Wood observed that the question of vibration was particularly important in the construction of flats and, as a large part of the housing programme would consist of flats, it was very important at the moment. Unfortunately the requirements of sound and vibration insulation involved cost, and since economy had to be considered in all the housing schemes, the provision of such insulation had to be reduced to the minimum. At present provision for expansion could be combined with the isolation of lift-shafts and stairs by a gap, but unfortunately insulation often had to be limited to that. Could the Authors state what percentage of the average cost of a block of flats would be entailed by the provision of vibration insulation of the nature set forth in the Paper?

Mr. A. S. E. Ackermann observed that the "ultimate bearing pressures" of clay given in Table III were beyond his comprehension. The vague terms "soft," "medium," and "hard" were used to describe the clay, instead of a statement of the percentage of water in the clay; but even that did not appear to account for bearing pressures of 2 tons or even 3 tons per square inch. In his experiments the stiffest clay had had a water-content of 17·5 per cent., and the pressure of fluidity was then only 10·5 tons per square foot. That clay was certainly stiff, if not nearly hard.

With regard to the statement (p. 15), that certain "cork pads must have a depth of 2 feet and be of very limited area"; would not that lead to the pads buckling?

Mr. Ackermann could not see any advantage in using two sheets of $\frac{1}{8}$ -inch lead. In fact, that appeared to be objectionable, because in time the lead would flow, as it had done in the jointing of the granite columns of Holborn Viaduct, causing the stone to spall off. The load on the lead was not given. His experiments had shown the pressure of fluidity of lead to be 4·93 tons per square inch.

The Authors had stated (p. 17) that a vibration of 0·001 inch was readily perceptible. In which direction was the vibration? Human beings found horizontal vibrations more annoying than vertical ones. That might be due to our early ancestors being used to the branch of a tree swaying up and down, but not so used to a sideways motion!

Mr. Ackermann was especially interested in *Fig. 33 (d)*, because for years he had tried to obtain the explanation of the following problem:¹

"If a very thin elastic rod, 9 inches in length, fixed at one end, swings as a pendulum, the expression $x(9 - x)^2$ measures the tendency of the rod to break at a place x inches from the point of suspension. From the graph, find where the rod is most likely to break."

¹ This and the following contributions were submitted in writing.—SEC. I.C.E.

¹ Hall and Knight, "Elementary Algebra," Examples xlv, f, No. 14.

The answer given was: "3 inches from the point of suspension." All engineers with whom Mr. Ackermann had discussed that problem had maintained that the maximum bending moment occurred at the point of fixture. He considered that, in doing so, they regarded only the first pull sideways as starting the oscillation, whereas the problem was concerned with the subsequent swinging, which was not the same. If it were accepted

that $B = x(l-x)^2 = x^3 - 2lx^2 + l^2x$, then $\frac{dB}{dx} = 3x^2 - 4lx + l^2 = 0$,

therefore, $x = \frac{1}{3}l$, which was the answer. It was true that *Fig. 33 (d)* showed an elastic holding of the member, and that the mode was one-third up from the bottom, so that the cases were not identical; but there appeared to be some connexion. $B = x(l-x)^2$ was stated, without proof, on p. 435 of "Elementary Algebra," 1946.

Dr. A. J. King observed that the Authors deserved the thanks of all structural engineers for collecting the information given in the Paper. Whilst expression (5) was true for a spring, it was not generally true for elastic supports, since in many cases the dynamic stiffness was greater than the static value. If the ratio of those two moduli, $Ed/E_s = k$, expression (5) would become ¹

$$\begin{aligned} n_0 &= \frac{1}{2\pi} \sqrt{\frac{kg}{\delta L}} \\ &= \sqrt{\frac{10k}{h}} \text{ approximately if } \delta L = h \text{ inches.} \end{aligned}$$

In practice, the value of k was approximately 2 for rubber, from 2 to 5 for cork, and up to 20 or more for felt.

In addition to expression (7), it was informative, from the point of view of the performance of vibration-detectors,² to give the corresponding expression for the displacement of m_2 relative to the other end of the spring (the compression of the spring), namely:—

$$\frac{N^2}{n_0^2 - N^2} e.$$

The Authors had indicated (p. 14) the necessity for obeying Hooke's Law for expression (5) to be true, but on p. 15 they had applied that expression to cork pads. A static compression of at least twice the $\frac{3}{8}$ inch given would be necessary to give a natural frequency of 5 cycles per second. The Authors' contrast with previous empirical designs echoed Dr. King's experience.²

An application of resilient mounting might be added to those given on p. 15, namely: a transformer weighing 100 tons resting on 3-inch

¹ A. J. King, "The Reduction of Structure-Borne Noise by Vibration-Attenuating Supports," *Engng. Lond.*, 29 July, and 12 Aug. 1938.

² A. J. King, "The Analysis of Vibration Problems," *J. I. E. E.*, vol. 93, part II, No. 35. (Oct. 1946).

thick rubber pads which effectively reduced the vibration transmitted to the ground and building by the desired amount.

The value of 15 per cent. given by the Authors for the damping coefficient of cork corresponded, following Zener,³ to a value for Q of

$$\frac{\pi}{0.15 \times 2} = 10.5.$$

That agreed roughly with Dr. King's values of Q for rubber² and cork. The differences between the Authors' figures of 18,500–49,000 lb. per square inch for Ed for felt and Dr. King's figures¹ of 3,000–6,000 lb. per square inch might be due partly to different samples and partly to the effect of the blows in the Authors' case.

Dr. King could not agree that cork was better than rubber for resilient mountings. The volumetric criterion L^2/Ed had been suggested² by him and, if desired, that could be changed to a cost basis by dividing by the cost per unit volume of the resilient material. Lateral flow in rubber was easily accommodated and oil and sunlight, which caused or accelerated deterioration, could usually be excluded. Dr. King has published^{1, 2} test data permitting a comparison of the elastic properties of rubber, cork, and felt.

Recently he had summarized briefly² the available information regarding the limits of human perception of vibration, and it had become apparent that a need existed for reliable information on that matter. A comprehensive investigation by a national laboratory would be very appropriate.

The Authors, in reply, observed that they had purposely confined the problem to that of a building subjected to impressed vibrations from underlying ground, that was, to oscillations imposed upon the spring/weight system at the bottom of the spring. The problem of how to deal with the reduction of vibrations into the ground at their origin was the opposite basic condition of that which the Authors had considered; there the oscillations were impressed on to the spring/weight system at the top of the weight, which rested on the spring. They hoped to deal with that matter more fully in a future paper.

The Authors agreed with the contention that a heavy sprung block of reinforced concrete, particularly where the reinforcement was very complicated, might be extremely expensive and they had found that a welded grillage or cradle connecting together the several parts of the installation was cheaper. Moreover, a welded structure of that type could be used to adjust the balance of the machine itself and of the whole spring/weight system.

The Authors considered that Mr. Husband's suggestion that "different compressors might propagate ground vibrations in different directions"

^{1, 2} *Loc. cit.*, p. 51.

³ C. Zener, "Internal Friction in Solids," *Proc. Phys. Soc.*, vol. 52 (1940), part I, p. 152.

was rather vague. Assuming the simpler case where complications occurred through the influence of adjacent strata, vertical vibrations induced into the ground were evenly and symmetrically radiated outwards. Similarly, rotational oscillations of the machine foundation purely in the horizontal plane gave rise to side shear or Love waves symmetrically in all directions—a kind of screwing action.

On the other hand, a machine oscillation purely in the horizontal plane along one dimension might be expected to produce only *P*-waves along that dimension, whilst at right angles there would be side shear, or Love waves, travelling outwards but with the oscillatory motion parallel to that of the *P*-waves. At intermediate angles the number of *P*-waves and Love waves would be proportional to the angle, either one or the other predominating according to position.

One of the Authors knew of a forge in Sheffield in which the hammer foundations had been set in rock with a considerable dip, consisting of thin layers of rock interspersed with thin layers of mud. The bases of the foundations were stepped to counteract any tendency to slip on that steeply-dipping rock. The foundations remained intact, but the underlying rock disintegrated so frequently that the whole forge had eventually to be moved to another site. It was probable that that failure had occurred through multiple reflexions and refractions of shock and other stress waves, mainly in tension, rather than by the much slower pressures from the oscillations of the spring-pad/anvil system.

A system where a whole building was set on suitably designed rollers for reducing horizontal earthquake accelerations, would work only within the limits of the general arrangement and the frictional resistance in the bearings or housing. That type of foundation would be quite suitable in earthquake zones if the direction of the tremor could be predicted within reasonable limits, for then only one set of rollers was needed, but if that were not possible, two sets at right angles and one above the other were necessary. One of the Authors had used that method in a building for taking up large continually altering temperature movements, but he regarded it as unsatisfactory for prolonged horizontal industrial frequency oscillation reduction because the rollers flatten and bite into the plate, and because of friction. That method was the logical development of those foundations which had been laid on a layer of "plastic" sand or gravel. The use of a large number of glass balls in a similar manner had been seriously advanced.

In the case of the Imperial Hotel, Tokyo, no plastic movement of the sand bed in the foundation had occurred during the 1923 earthquake,† where the recorded horizontal accelerations were of the order of $\frac{1}{4}g$. That appeared to confirm the Authors' contention that sand and gravel, under the action of low-frequency vibrations, had properties similar to those of the surrounding ground.

† In spite of a biography which stated the contrary.

Dr. Rankine had raised an interesting point about the behaviour of the ground immediately at and adjacent to the point of impact or oscillation on or near the surface of the ground. One of the Authors had recently developed a theory to account for the observed phenomena, and he was unable to find that any physicists or others had investigated that problem very much so far. He hoped to publish that theory later.

The Authors strongly endorsed Mr. Lankshear's plea for an adequate knowledge of the behaviour of cork under vibration, and they hoped with him that before long such knowledge would be readily available to the practical engineer. Recently they had learned that it was hoped to carry out dynamic oscillation measurements on materials in Zürich. Examples of cork-sprung foundations in Holland and Germany showed that efforts had been made to keep the cork dry in foundations, and to arrange details so that it could easily be removed and replaced when it became hard.

Conflicting measurements of the dynamic elastic modulus had been made in the United States, which indicated that the dynamic modulus of cork could be less than its static modulus. It seemed that successful cork springs might be applied to structural work, provided that adequate vibrational measurements were carried out beforehand, without placing too much reliance on calculations based upon the present inadequate evidence.

Mr. Gray's figures of amplitude reduction by means of springs and cork, though interesting, did not take into account any possible change in ground frequency response which might have taken place. For the machine weighing 110 tons mounted on very soft compressed-air springs, and with dead beat oil damping, when either of those aids was disconnected, the natural ground frequency of 25 cycles per second was noticeable; when both were in circuit, the natural ground frequency appeared to have been unexpectedly eliminated. Vibration remaining in the ground was of much lower frequency as well as being of smaller amplitude. Further research was warranted there.

More suitable anti-vibration mountings appeared to be oil or mechanical springs, since compressed-air springs suffered from leakage. The method of calculating an air spring was to use Boyle's law, but small complications arose through increase in temperature, possible frothing between air and oil, and overheating internally in the dashpots. Those tend to make the system expensive and the Authors considered that it was not the best line of development.

From the engineering point of view the Authors distinguished three classes of ground vibrations with which a designer should be prepared to deal. The steady series of waves (*a*) were straightforward; the more complex train of waves (*b*) which developed at a distance remote from the source of impact or single impulse, such as a forging hammer, had already been described, but they were fairly gentle in comparison with the shock wave (*c*), which was important only close to the centre, but not at a

distance. In types (a) and (b) there were no violent changes in ground movement, amplitude, frequency, or acceleration. In type (c) the ground at the centre moved suddenly under the influence of the sudden impulse, as in *Fig. 50*, the ensuing oscillation dying out after a few cycles. That sudden springing into movement had a very high momentary acceleration, as seen at "X" in the illustration, but it was followed by more gentle accelerations, the retardations being in phase with the displacements.

Fig. 50.

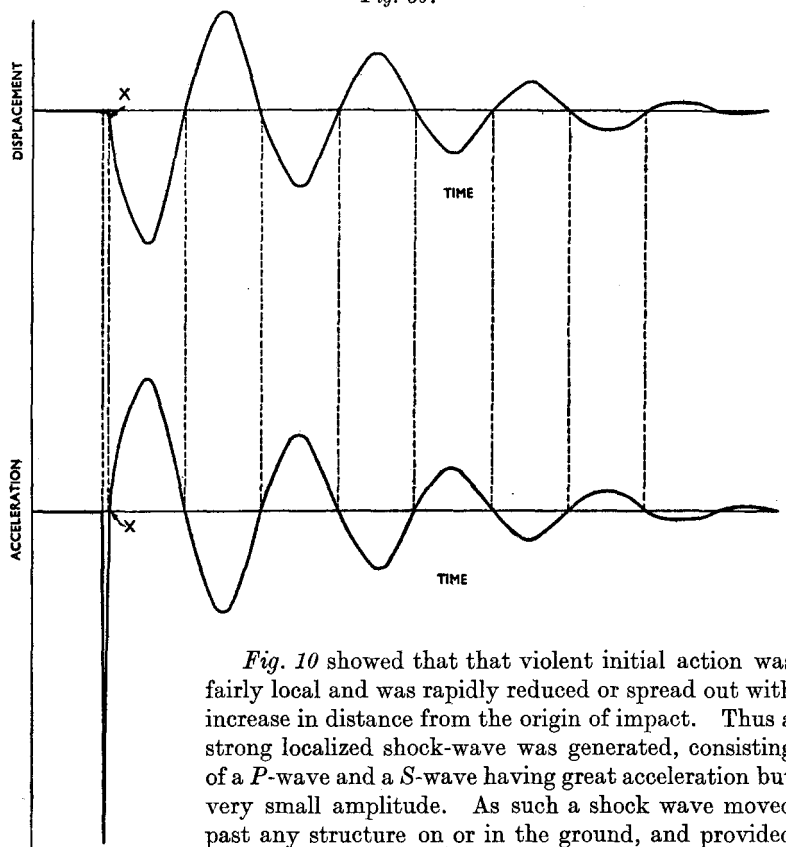


Fig. 10 showed that that violent initial action was fairly local and was rapidly reduced or spread out with increase in distance from the origin of impact. Thus a strong localized shock-wave was generated, consisting of a *P*-wave and a *S*-wave having great acceleration but very small amplitude. As such a shock wave moved past any structure on or in the ground, and provided that the amplitude of the wave at a relevant part of its travel was still sufficiently large to be important, it would have the effect of giving the structure a blow, and that blow would set the structure into motion at its own natural frequency of vibration. No trouble arose in the industrial cases met with from a building having the same frequency as the shock-wave, because the latter was too short and too transitory to allow of any resonance building up. However, if the structure and the ground happened to have the same or nearly the same natural frequency

at that place, then the shock wave would set both into oscillation and the resulting resonant oscillations, or near resonant oscillations, between the two might inflict structural damage. That was in strong contrast to cases (a) and (b), where the structure was induced to oscillate at the same frequency as that of the train of waves in the ground at all times during the train, and not at its own natural frequency, except as a secondary effect, during starting, changing speed, or stopping in case (a), and during the several changes occurring in case (b).

In Mr. Grey's case, the forging hammer was set on limestone and it might be assumed that the base of the anvil rested on the usual timber spring pad, which formed a part of the whole spring system acting to bring the anvil to rest after it had been stuck in the vertical direction. If the combined weight of the anvil, the foundation, and the active ground underneath and around the foundation were relatively small, its resulting initial velocity would be correspondingly large, as at "X" in *Fig. 50*. The initial acceleration would therefore be large, and it followed that the shock-wave impressed into the ground would also be large in intensity. That velocity was independent of the resilience of the spring pad placed under the anvil and of the ground. It should be added that a short, sharp hammer-blow caused a sharper shock-wave in the ground than if the blow were gentle, although in the latter case the blow could deliver more energy than in the former because its duration could be much longer.

Foundation and ground, having been thus set in motion, would move downward until the combined spring effect of the ground, etc., was high enough to stop the motion and then reverse it, thereby producing several rapidly dying out strong oscillations. The relative resilience and density of the strata had a considerable influence upon the subsequent movements. If the impacting machine foundation rested on rock, its resilience contributed little to the combined spring effect and the amplitude of local oscillations set up in the rock was thus comparatively small; the resulting waves radiating outward in the rock stratum should also be fairly small. On the other hand, if such a foundation were mounted in a soft, relatively thick claystratum overlying rock, then the combined spring was much softer than before and the combined total local oscillations were of much greater amplitude. Therefore much larger waves were radiated in the upper clay stratum, whilst those in the deeper rock would be much smaller. The most usual case in practice was that in which a soft surface layer overlay a harder lower stratum, and the Authors had therefore tabulated the general expected theoretical ground effects according to the exposition of them in the Paper. They seem to bear out reasonably well the results obtained by the Authors. Table VII indicated the kind, quantity, and intensity of vibration in each stratum, near to and remove from the centre, and for both small and large shocks, which might be imparted either by impulsive machines or by blasting. That very approximate tabular guide indicated that for a machine imparting sudden impulses into the ground, if there

TABLE VII.

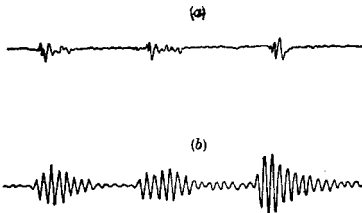
5 PROPORTIONS OF SHOCK WAVE AND OSCILLATION WAVES IN A SOFT UPPER STRATUM AND IN A HARD UNDERLYING STRATUM, PRODUCED BY SUDDEN IMPULSE.

IF MACHINE FOUNDATION is on, or BLASTING CHARGE is in :—	IF RELATIVE SIZE OF ORIGINAL SHOCK IS :—			
	HIGH : by initial velocity and shock from SMALL foundation and active ground, or SHATTERING BLAST CHARGE, THEN :—		Low : by initial velocity and shock from LARGE foundation and active ground, or SLOW BLAST CHARGE, THEN :—	
	Near to centre	Remote from centre	Near to centre	Remote from centre
UPPER SOFT STRATUM	Vibrations in soft upper stratum ; very strong shock wave few strong oscillations	many mod. oscns.	Vibrations in soft upper stratum ; strong shock wave few mod. oscillations	many weak oscns.
	Vibrations in hard lower stratum ; mod. shock wave few weak oscillations	several weak oscns.	Vibrations in hard lower stratum ; weak shock wave few weak oscillations	several feeble oscns.
LOWER HARD STRATUM	Vibrations in soft upper stratum ; mod. shock wave few weak oscillations	many weak oscns.	Vibrations in soft upper stratum ; feeble shock wave few weak oscillations	many feeble oscns.
	Vibrations in hard lower stratum ; very strong shock wave few mod. oscillations	several feeble oscns.	Vibrations in hard lower stratum ; moderate shock wave few feeble oscillations	several very feeble oscillations

NOTE.—The comparative words used above are roughly in the orders of amplitude of : “ very strong,” “ strong,” “ moderate,” “ weak,” “ feeble,” “ very feeble,” and “ many, several, few,” for the number of cycles in the train of waves and oscillations as discussed in the Paper.

were to be a minimum disturbance to local property, and if a special anti-vibration foundation were not desired in either the machine or the building, the best results would be obtained by mounting the machine on a large weight of combined foundation and active ground, founding it on the lower hard stratum, whilst adjacent buildings might be either on the soft upper or the hard lower strata, and the remote buildings could best be on the lower hard stratum and be preferably isolated from the upper. The type of building was important, however, because those built in, say, lime mortar might easily suffer from shear failure if subjected to a moderate shock wave, and it might be better to select another stratum carrying less shock but more oscillations. Those might produce different kinds of progressive failure, and in the Author's view, an investigation into their main features was long overdue. Unfortunately, no vibrographic readings or other satisfactory examination was made of the house which collapsed,

Fig. 51.



VERTICAL (a) AND HORIZONTAL (b) MOVEMENTS IN A BUILDING INDUCED BY GROUND VIBRATIONS FROM AN ADJACENT PILE-DRIVER.

but the Authors hoped shortly to gather together any information which still remained.

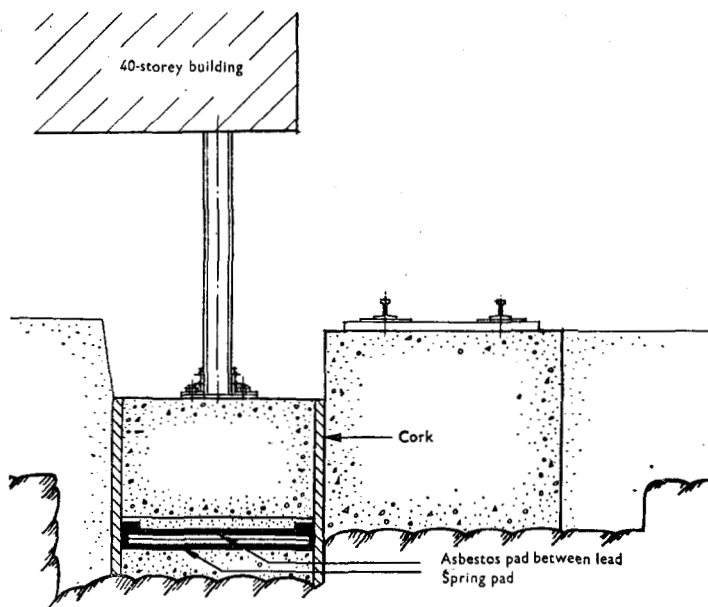
In replying to Dr. Rankine's inquiry as to the most dangerous type of ground vibration, the Authors did not know whether any one kind was more so than another. Danger of collapse from industrial sources in Great Britain was slight, but considerable fatigue and other cumulative effects occurred in whole structures and portions of them; evidence was usually provided by cracks and slight

shifting. Even though no damage might occur at once, it might eventually become apparent owing to fatigue, etc., from the strong build-up which could take place by virtue of the low damping coefficients of most materials and methods; the Authors had had experience of one structure where the amplitude was increased more than 200 times for a very near resonance. Circumstances should determine the nature of the most dangerous type of ground vibration; the horizontal vibrogram in *Fig. 51* was of the horizontal movement at the top of a building produced by pile-driving some distance away, in which there was apparent a build-up during several cycles induced by the train of ground waves at that distance from the centre, although the original impulse had consisted of a single blow.

The Authors agreed with Mr. Andrews that asbestos fibre could provide a very satisfactory spring, more particularly under damp conditions where the load was high and where the material was required to last a long time; at present less physical data were available than for cork. In New York

the owners of buildings adjacent to the Grand Central station had taken steps to eliminate the ground vibrations from trains about 25 years ago. After experiments, insulation had been provided by a multiple sandwich, as already described; that was arranged as shown diagrammatically in *Fig. 52*, and cork slabs surrounded the concrete base and stanchions. The disappointing results gave rise to research to determine the optimum asbestos fibre thickness. Those tests had not included measurements of resilience in the horizontal dimensions, but they did show that a $\frac{1}{2}$ -inch spring pad of asbestos fibre under normal foundation pressures provided

Fig. 52.



INSULATION DIAGRAM, GRAND CENTRAL STATION, NEW YORK.

practically negligible insulation at the usual frequencies, whereas a 10-inch thickness of the compound asbestos and lead sandwich gave much better results in the vertical dimension. Incidentally, a 2-foot thickness of sand was tested, but was found to be of no use at all as a resilient spring.

The Authors were interested to learn that Mr. Allen believed that the measures suggested by them were likely to find a much wider application than they had suggested.

After further study, it appeared that rubber was a very suitable and economical material and might need replacement only once or twice during

the life of a building. The Authors were glad to learn about the proposed research on the effect of ground vibrations transmitted into structures at the Building Research Station and would like to keep in touch with every phase of the work.

In reply to Mr. Wood, the Paper was concerned only with principles, but the number of applications in existence had demonstrated that some clients had considered such insulation worth while on cost.

Mr. Ackerman's question about the possible buckling of a long thin spring of cork accented the need for binding that type of spring with bands or plates of sheet steel ; those would not seriously affect the spring constant, because the frictional force was always relatively small, irrespective of the overall compression. The gap in that binding at each end should be large enough to accommodate both lateral movements and progressive consolidation in service. The cork pads for the machine illustrated in *Fig. 46* could be easily and rapidly renewed.

The very thin elastic rod, fixed at one end, was a built-in cantilever and did not behave as a pendulum ; moreover, being very thin, it was not an engineering structure. The Authors had noticed that monkeys up trees described extremely complicated motions ; they were not competent to judge the extent to which probably arboreal instincts had influenced recent generations of mankind !

The Authors were very grateful to Dr. King for his valuable contribution, and they agreed with him ; they thoroughly endorsed his contention of the need for investigation into vibration perception limits for human beings.

Further information had been obtained which helped to clarify the problem of trenches used for insulation of ground vibrations. The depth of the surface waves was a function of the wavelength and frequency. For a certain ravine with steep sides, 50 feet deep, with a railway near one edge, there was still a noticeable proportion of the vibrations of the train transmitted to the other side. Frequencies commonly induced into the ground by trains had a range from about 5 cycles to 150 cycles per second, which was of a similar order to those induced by road traffic, heavy industrial plant, and blasting. Ground oscillations of from half a cycle to two cycles per second due to bomb explosions were often easily perceptible to people in the London Underground shelters at a depth of 200 feet. In mines of more than a mile deep, earthquake oscillations with an approximate range of from half a cycle to one cycle per second, were often quite perceptible ; but considerable earthquakes, which had caused much damage on the surface, had not always been felt by workmen at very great depths, possibly because the men were working and causing masking effects. However, that very approximate scale should be treated with caution, in view of the influence of varying strata.