EFFECTS PRODUCED BY EARTHQUAKES UPON BUILDINGS.

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(An abstract, with additions and corrections, from Chaps. VI. and VII., of Milne's "Earthquakes," International Scientific Series, Vol. LVI., written in 1883).

Contents.—The destruction of buildings is not irregular—Cracks in buildings—Buildings in Tokio—Relation of destruction to earthquake motion—Measurement of relative motion of parts of a building shaken by an earthquake—Prevention of cracks—Direction of cracks—The pitch of roofs—Relative position of openings in a wall—The last house in a row—The swing of buildings—Principle of relative vibrational periods—Types of buildings used in earthquake countries—In Japan, in Italy, in South America, in Caraccas—Typical houses for earthquake countries—Destruction due to the nature of underlying rocks—The swing of mountains—Want of support on the face of hills—Earthquake shadows—Destruction due to the interference of waves—Earthquake bridges—Examples of earthquake effects—Protection of buildings—General conclusions.

The subject of this chapter is, from a practical point of view, one of the most important with which a seismologist has to deal. We cannot prevent the occurrence of earthquakes, and we have not the means of escaping from them unless we avoid earthquake-shaken regions. What we can do, however, is in some degree to protect ourselves. By studying the effects produced by earthquakes upon buildings of different construction, and variously situated, we are taught how to avoid or at least to mitigate calamities which, in certain regions of the world, are continually repeated. The subject is an extensive one, and what is here said about it must be regarded only as a contribution to the work of future writers, who may give it the attention it deservedly requires.

THE DESTRUCTION PRODUCED BY EARTHQUAKES IS NOT IRREGULAR.—If we were suddenly placed amongst the ruins of a large city which had been shattered by an earthquake, it is doubtful whether we should at once recognise any law as to the relative position of the masses of *débris*, and the general destruction with which we are surrounded. The results of observation have, however, shown us that, amongst the apparently chaotic ruin produced by earthquakes, there exists in many cases more or less law governing the position of bodies which have fallen, the direction and position of cracks in walls, and the various other phenomena which result from such destructive disturbances.

Mallet, at the commencement of his first volume, describing the Neapolitan earthquake of 1857, discusses the general effect produced by various shocks upon differently constructed buildings. First he shows that, if we have a rectangular building, the walls at right angles to the shock will be more likely to be overthrown than those which are parallel to it. Experience teaches a similar lesson. Thus Darwin, when speaking of the earthquake at Concepcion in 1835,* tells us that the town was built in the usual Spanish fashion, with all the streets running at right angles to each other. One set ranged S.W. by W. and N.E. by E. and the other N.W. by N. and S.E. by S. The walls in the former direction certainly stood better than those in the latter. The undulations came from the S.W.

CRACKS IN BUILDINGS.—Results like the above come from destructive earthquakes rather than from movements such as those we have to deal with ordinarily. When a building is subjected to a slight movement, it is assumed that the walls at

* Here certain matter relating to the houses in Caraccas extracted from H. D. Warner's paper, "The City of Earthquakes" (*Atlantic Monthly*, March, 1883), has been omitted, as I have reason for believing that much of the matter in that paper is incorrect.—J.M.

right angles to the direction of the shock move backwards and forwards as a whole, and there is little or no tendency for them to be fractured at their weaker parts, these weaker parts being those over the various openings. The walls, however, which are parallel to the direction of the movement are, so to speak, extended and contracted along their length, and in consequence they may be expected to give way over the various openings. This tendency of a wall to extend and contract along its length may be supposed, for instance, to be due to the different portions of a wall having different periods of natural vibration owing to differences in dimensions and elasticity, or possibly to the fact of two portions of a long line of wall being simultaneously affected by portions of waves in different phases.

As an illustration of the giving way of a building in the manner here suggested, we may take the case of a large brick structure which was recently being erected in Tokio (the Imperial Palace at Akasaka). This building, at the time of the earthquake, was only some fourteen or fifteen feet above the surface of the ground. The length of the building stretched from N.W. to S.E., and it was intersected by many walls at right angles to this direction. Through all the walls of this building there were many arched openings. In the central part of the transverse walls, which were fully five feet in thickness, the arches joining them together were 4 feet 4 inches in thickness. The arches therefore formed a comparatively lightly constructed link between heavy masses of brickwork.

On March 3rd, 1879, at 4.43 p.m., an earthquake was felt throughout Tokio, the strength of which, as judged by our feelings, was above that of an average shock. As registered by one of Palmieri's instruments, it had a direction S.S.W. to N.N.E. and an intensity of 11°. On the same day there were several smaller shocks having the same direction, and these were succeeded by others on the 9th of the month.

Immediately after these shakings it was discovered that almost every arch in the internal walls of the building here referred to had been cracked across the crown in a direction about N. 40° W. All the other arches of the building, of which there were a great number in walls at right angles to the direction of the shock, were found not to have sustained any injury. To this result, however, there was one exception, which was subsequently proved to have been due to a settlement taking place.

After examining these cracks the only cause to which they could be attributed was the series of shakings which they had just experienced. It seemed as if the heavy walls right and left of the arches had been in vibration without synchronism in heir periods, and as a consequence the arches which connected them had been torn asunder.

Although the time at which the cracks were formed, and the peculiar positions in which they were alone to be found, pointed distinctly to their origin, in order to be quite certain that they were not due to settlements in the foundations, horizontal lines were ruled upon the brickwork and from time to time subsequent observations were made.

The points to which the various cracks extended were also marked and observed. Beneath the walls as foundations there were beds of concrete about three feet thick and about ten feet in width. These had been under the pressure of the partially built walls for two years before the arches had been put in. As these foundations were unusually strong, being intended to carry a very much greater weight than that to which they had been subjected, if any settlement had been detected it would have been a matter of surprise.

Some weeks after the formation of these cracks it was observed that they gradually closed. This was probably due to the gradual falling inwards of the two broken portions of the arch, their position when open being one of instability.

Had this building been more complete at the time of the shock, and the heavy walls been tied together at higher points, although the archways would have been points of weakness, it is quite possible that fracture would not have taken place. This illustration shows us that when a building is shaken in a definite direction there will be some rule as to the positions in which fractures occur. As another example, we may take the observations of Alexander Bittner upon the buildings of Belluno after the shock of June 29th, 1873 (see Beiträge zur Kenntniss des Erdbebens von Belluno am 29 Juni, 1873, p. 40. Von Alexander Bittner. Aus dem LXXI. Band der Sitzungsb. der K. Akad. der Wissensch., II. Abth., April-Heft. gahrg. 1874).

Speaking generally, he remarks that "Houses similarly situated have suffered in corresponding walls and corners in a similar manner. In Belluno there is a certain kind of damage which is repeated everywhere, making a peculiar system of splits in the S.W. and N.E. corners of the houses."

Buildings in Tokio.—For the purpose of finding out what has been the effect produced by earthquakes upon the buildings of Tokio, and at the same time in order to ascertain whether blocks of buildings ranging in different directions suffered to the same extent, the author examined, in company with Mr. Josiah Conder, Government Architect, a large number of foreign-built houses in the district of the Ginza. The chief reason for choosing this locality was because it was the only district where a large number of *similar* buildings could be found. By examining houses or buildings of different constructions, the effects produced upon them by earthquakes are very often likely to show so many differences that it becomes almost an impossibility to determine what the general effect has been—unsymmetrical construction involving unsymmetrical ruin.

A number of similarly constructed buildings in one locality may be regarded as a number of seismographs, the effect upon any one of them being judged of by the average of the general effect which has been produced upon the whole. These houses are built of brick, and are in many cases faced with a thin coat of white plaster. Projecting from the level of the upper floor there is a balcony fronted by a low balustrade. This is supported by small beams which at their outer extremity are carried on a row of cylindrical columns, the arrangement forming a covered way in front of each row of houses. The roofs are covered with thick tiles. It will be observed that the arches of the upper windows spring *sharply* from their abutments, and at their crown they carry a heavy key-stone. The lower openings, which have a span of 9 feet, have evidently been constructed in imitation of the open front of an ordinary Japanese house. These archways curve out *gently* from their abutments. The outside walls have a thickness of 13½ inches.

The results obtained from a careful examination of 174 houses in streets running N.E. and 156 houses in streets running N.W., all of these houses being similar, were as follows :—

1. In the upper windows nearly all the cracks ran from the springing, which formed an angle with the abutment.

2. In the lower arches, which *curved* into the abutments, not a single crack was observed at the springing. The cracks in these arches were near the crown, where beams projected to carry the balcony. In many instances the cracks proceeded from such beams, even if there were no arch beneath. That cracks should occur in peculiar positions, such as here indicated, is shown in the illustrations which accompany the accounts of many earthquakes.

3. The houses which were most cracked were in the streets running parallel to the direction in which the greater number and most powerful set of shocks cross the city.

The results showed that, in order to avoid the effects of small shocks, all walls containing principal openings should be placed as nearly as possible at right angles to the direction in which the shocks of the districts usually travel. The blank walls, or those containing unimportant openings, would then be parallel to the direction of the shocks—that is, presuming our buildings to be made up of two sets of walls at right angles to each other.

Another point of importance would be to build archways *curving* into the supporting buttresses; the archways over doors and windows which we find in earthquake countries do not appear to be in any way different from those which are built in countries free from earthquakes. In the one country these structures have simply to withstand vertical pressures applied statically; in the other, they have to withstand more or less horizontal stresses, applied suddenly.

RELATION OF DESTRUCTION TO EARTHQUAKE MOTION.—The relations which exist between the overturning and projection of bodies and the motion of the ground have already been discussed. It may be interesting to call attention to the fact that in the formulæ showing three relationships, it was the *shape* rather than the *weight* of a body which determined whether it should be overturned or projected by a motion at its base.

As an interesting proof that light bodies may be overturned as easily as heavy ones, Mallet refers to the overturning of several large haystacks as one of the results of the Neapolitan earthquake.

If masses of material are displaced or fractured, then Mallet remarks that the maximum velocity will exceed $\sqrt{2gh}$, where h is the amplitude of the wave. Should the maximum velocity be less than this quantity, the masses which are acted upon will be simply raised and lowered, and there will be no relative displacements even if the emergence of the wave be nearly or quite vertical.

When we get a vertical wave acting upon an irregular mass of masonry, the heavier portions of the masonry, by their inertia, tend to descend relatively to the remaining portions, and in this way vertical fissures will be produced. For this reason it would not be advisable to use heavy materials above archways, heavy roofs, or heavy floors. The vertical fissures, Mallet remarks, would have their widest opening at the base.

In considering cases of fracture produced by earthquake motion, it must be remembered that these are due to stresses applied *suddenly*, and that if the same amount of stress had been *slowly* applied to a building, fractures might not have occurred.

If a disturbance is horizontal, and has a direction parallel to the length of a wall, the wall is carried forward at its foundations. This motion is opposed by the inertia of the upper portion of the wall and the various loads it carries. The wall being elastic, distortion takes place, and cracks, which are widest at the top, will be formed. In a uniform wall the two most prominent fissures ought to be near the ends.

If the horizontal backward and forward movement has a direction oblique to the plane of the wall, the wall will be either overthrown, fractured, or have a triangular fragment thrown off towards the origin from the end last reached.

Should the wave emerge steeply, diagonal fissures at right angles to the direction of transit will be formed, or else triangular pieces will be projected.

It might be argued that the direction of these fractures was due to the direction in which surface undulations had travelled, or to the relative strengths and proportions of different portions of the building. The directions of cracks in a building are undoubtedly due to a complexity of causes, but for buildings situated in the region of shock the impulsive effect of the shock is probably the most important function to be considered. The method of applying the directions of emergence, deduced from observations on fractures, to determine the origin of a disturbance will be referred to in Chapter X.

Mallet observed that, although two ends of a building might be nearly the same, the fissures and joints do not occur at equal distances from the ends, nor are they equally opened.

The end where the joints are the most opened is that which was first acted upon, and this phenomenon may be sufficiently well pronounced to indicate the direction in which we must look to find the origin of a disturbance. Amongst possible explanations for this disposition of fractures in a wall, Mallet suggests that they may be due to real differences in the two semiphases of the wave of shock, the second semiphase being described with a somewhat slower velocity than the first. This, it will be observed, is contrary to the indications of seismographs. Corners of buildings are often destroyed.

Measurement of the Relative Motion of the Parts of a Building at the time of an Earthquake.

In 1880 a series of observations was made in Tokio to determine whether at the time of an earthquake the various parts of the arched openings which we see in many buildings synchronised in their vibrations, or, for want of synchronism, were caused to approach and recede from each other. The arches experimented on were heavy brick arches forming the two corridors of the Imperial College of Engineering. The direction of one set of these corridors is N. 40° E. and that of the other N. 50° W.

The thickness of the walls in which these arches are placed is 1 ft. 11 in. They are built of Japanese bricks, bound together with ordinary lime mortar. The span of the arches is 8 ft. 3 in., and the height of the arch from the springing-line to the crown 4 ft. 1 in. The height of the abutments is 7 ft. $1\frac{1}{2}$ in. The voussoirs of the arch are formed of a light grey soft volcanic rock, and on their faces show a depth of 12 inches. The width of the intermediate columns between the arches is 4 ft. $6\frac{7}{8}$ in.

To determine whether at the time of an earthquake there was any variation in the dimensions of these arches, a light stiff deal rod, about 2 in. by $\frac{1}{2}$ in. in cross section, was placed across the springing-line of the arch. One end of this was firmly fixed to the top of one abutment by means of a spike; on the other end, which was to indicate any horizontal movement if the abutments approached each other, there was fixed a pointer made out of a piece of steel wire. This rested on a piece of smoked glass fixed to the ledge on which the loose end of the rod was resting. If the abutments approached or receded from each other a line would be drawn measuring the extent of the motion. As a further indication of motion, a second smoked glass plate was fixed on the transverse rod, which plate was marked on by a pointer attached to a vertical rod hanging down from the crown of the arch.

As a general result of these experiments it may be said that the portions of the building which were examined usually either did not move at all, or else they practically synchronised in their movements. When they did move, the extent of motion was small, and the small differences in movement which were observed were in every probability far within the elastic limits of the structure.

Observations on Cracks.—To determine whether the walls of a building which have once been cracked, when subjected to a series of shocks, similar to those which they experienced before being cracked, still continued to give way, the extremities of a considerable number of cracks in the N.E. of the museum buildings of the Engineering College were marked with pencil. Although since the time of marking there had been many severe shocks, these cracks did not visibly extend. These marks were made on the outside wall of the building. On the inside, one of these same cracks showed itself as a fissure about $\frac{1}{4}$ inch in width. Across this crack a horizontal steel wire pointer was placed. One end of this wire was fixed in the wall; the other end, which was pointed, rested on the surface of a smoked glass plate placed on the other side of the crack. After small earthquakes there was no indication of motion having taken place, but after a shock on February 21st, as indicated by a line upon the smoked glass plate, it was seen that the sides of the crack had approached and ~~and~~ receded from each other through a distance of about $\frac{1}{16}$ inch.

By similar contrivances placed on cracks in a neighbouring building, exactly similar results were obtained, namely, that during small earthquakes the two sides of the crack had retained their relative position, but at the time of a large shock this position had been changed.

In this building it was also observed that the cracks in many instances increased their length.

By attaching levers to the end of the pointers to multiply any motion that might take place, no doubt the indications would be more frequent and more definite. It would also be easier to note the relative distances of motion in two directions, namely, how far the cracks had closed and how far they had opened. As to whether motion would occur or not, much would no doubt depend upon the direction of the earthquake.

Prevention of Fractures.—One conclusion which may perhaps be drawn from these observations is, that a cracked building at the time of an earthquake shows a certain amount of flexibility. Whether a building which had been designed with cracks or joints between those parts which were likely to have different periods of vibration would be more stable, so far as earthquake shakings are concerned, than a similar building put up in an ordinary manner, is a matter to be decided by experiment. Certainly some of the cracks which have been examined indicate that if they had not existed, the strain upon the portion of the building where they occur would have been extremely great.

Direction of Cracks.—In looking at the cracks produced by small earthquakes it is interesting to note the manner of their extension. The basements of the buildings which have been most carefully examined are, for a height of two or three feet, built of large rectangular blocks of a greyish-coloured volcanic rock. In these parts the cracks pass in and out between the joints of the stone, indicating that the stones have evidently been stronger than the mortar which bound them together, and as a consequence the latter had to give way. Above this basement, when the cracks enter the brickwork, they no longer exclusively confine themselves to the joints, but run in an irregular line through all they meet with, sometimes through the mortar joints. In places, where they have traversed the brickwork, we can say that the mortar has been stronger than the bricks. This traversing of the bricks rather than the joints is, I think, the general rule for the direction of of the cracks in the brickwork of Tokio buildings.

THE PITCH OF ROOFS.—From observation of the effects produced by earthquakes, it appears to us that the houses which lost the greater number of tiles appear to be those with the steepest pitch, and those where the tiles were simply laid upon the roof and not in any manner fastened down. It would seem that destruction of this sort might to a great extent be obviated by giving the roofs a less inclination and fixing the tiles with nails. It was also noticed that the greatest disturbance amongst the tiles was upon the ridges of the roofs. Destruction of this sort might be overcome by giving especial attention to these portions during the construction of the roof.

RELATIVE POSITION OF OPENINGS IN WALLS.—From what has been said about the fractures in the buildings of Tokio it will have been seen that, with but few exceptions, they have all taken place above openings like doorways and windows. If architecture demands that openings like arches should be placed one above another in heavy walls of this kind there will be lines of weakness running through the openings parallel to the dotted lines indicated in Plate. As arches are only intended to resist vertical thrusts, special construction must be adopted to make them strong enough to resist horizontal pulls. For instance, a flat arch would offer more resistance to horizontal pulls than an arch put together with ordinary voussoirs, there being in the former case more friction to prevent the component parts sliding over each other. Or again, above each arch an iron girder or wooden lintel might be inserted in the brick or stone arch. It was suggested to me by my colleague, Mr. Perry, that the best form calculated to give a wall uniform strength, would be to build it so that the openings of each tier would occupy alternate positions, that is to say, along lines parallel to the struts and ties of a girder. In this way we should have our materials so arranged that they would offer the same resistance to horizontal as to vertical movements. Such a wall is shown in fig. 20: the dotted lines running through the openings, and all similar lines parallel to the former, representing lines of weakness. If we compare this with fig. 21, we shall see that in the case of a horizontal movement *a b*, or of a vertical movement *c d*, we should rather expect to find fractures in a house built like fig. 21 than in one built like fig. 20. If, however, these two buildings were shaken by a shock which had an angle of emergence of about 45° in the direction *e f*, the effects might be reversed. Usually, however, and always in a town like Tokio, which is visited by shocks originating at a distance, the movements are practically horizontal ones, and, therefore, buildings erected on the principles illustrated by fig. 20 should be much superior, so far as resisting earthquakes is concerned, to buildings constructed in the ordinary manner, as in fig. 21.

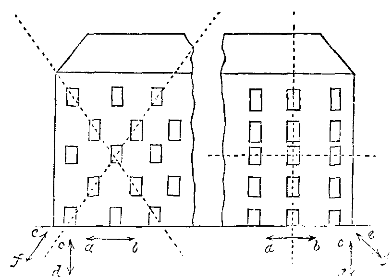

FIG. 20. FIG. 21.

I have photographs of many buildings that have been shattered by earthquakes.

THE LAST HOUSE IN A ROW.—When an earthquake shock enters a line of buildings, and proceeds in a direction coincident with that of the buildings, we should expect that the last of these houses, being unsupported on one side, would be in the position of the last person in Tyndall's row of boys. From this it would seem that the end house in a row would show the greatest tendency to fly away from its neighbours. If the last house stood upon the edge of a deep canal or a cliff, there would be a layer of ground, equal in thickness to the depth of the canal or to the height of the cliff, as the case may be, which would also be in a position to be thrown forward. Judging from photographs of buildings damaged by earthquakes this kind of destruction is not uncommon.

THE SWING OF BUILDINGS.—The distance through which buildings are moved at the time of an earthquake depends partly on their construction and partly on the extent, nature, and duration of the movement communicated to them at their foundations. By violent shocks buildings may be completely overthrown. In the case of small earthquakes, the upper portion of a house may frequently move through a much greater distance than the ground at its foundation. For instance, during the Yokohama earthquake of February, 1880, when the maximum amplitude of the earth's motion was probably under $\frac{3}{4}$ of an inch, from observation of the slow swing of long Japanese pictures, from three or six feet in length, which oscillated backwards and forwards on the wall, it appeared very probable that the extent through which the upper portion of houses moved was very considerable. In some instances these pictures seem to have swung as much as two feet, and from the manner in which they swung they evidently synchronised with the natural swing of the house.

From this it would seem that such a house must have rocked from side to side one foot out of its normal perpendicular position. That the motion was great is testified by nearly all who tried to stand at the time of the shock, it having been impossible to walk steadily across the floor of a room in an upper story. The houses here referred to are either those which are purely Japanese, or else those which are framed of wood and built on European models, a class of building which is very common in Tokio and Yokohama.

Perry and Ayrton calculated the period of a complete natural vibration of different structures. For a square house whose outer and inner sections were respectively 30 and 26 feet, the period calculated would be about ·06 second.

At the time of the above earthquake many houses seem to have moved like inverted pendulums. On the morning after the shock my neighbour, who was living upstairs under a tile roof, told me that he endeavoured to count the vibrations, and was of the impression that to make a complete swing it took about 2 seconds.

Assuming now that the distance through which the top of a wooden house moved was about 1 foot, and the number of vibrations which it made per second was about ·5, then the greatest velocity of a point on the top of such a house must have been about 6 feet per second.

Mallet, who made observations upon the vibrations of various structures, tells us that Salisbury spire moves to and fro in a gale more than 3 inches. A well-constructed brick and mortar wall, 40 feet high and 1 foot 6 inches thick, was observed to vibrate in a gale 2 feet transversely before it fell.

An octagonal chimney with a heavy granite capping, 160 feet high, was observed instrumentally to vibrate at the top nearly 5 inches.*

At the time of a severe earthquake it does not seem impossible that a building might be swung completely over. I have a photograph illustrating such a phenomenon.

Principle of relative Vibrational Period.—If a lath or thin pole loaded at one end with a weight and fixed to the ground, so as to stand vertically, be shaken by an earthquake it will be caused to rock to and fro like an inverted pendulum. The period of its swing will be chiefly dependent on its dimensions,

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* Mallet *Dynamics of Earthquakes.*

its elasticity, and its load. In a building we have to consider the vibration of a number of parts, the periods of which, if they were independent of each other, would be different. On account of this difference in period, whilst one portion of a building is endeavouring to move towards the right, another is pulling towards the left, and, in consequence, either the bonds which join them or else the masses themselves are strained or broken. This was strikingly illustrated by many of the chimneys in the houses at Yokohama, which by the earthquake of February 20th, 1880, were shorn off just above the roof. The chimneys were shafts of brick, and probably had a slower period of vibration than the roof through which they passed, this latter vibrating with the main portion of the house, which was framed of wood.

A particularly instructive example of this kind which came under my notice is roughly sketched in fig. 25.

This is a chimney standing alone, which, for the sake of support, was strapped by an iron band to an adjoining building. It would seem that at the time of the shock, the building moving one way and the chimney another, the swing of the heavy building gave the chimney a sharp jerk and cut off the iron connection. The upper portion, being then loose upon the lower part, rotated under the influence of the oscillations in a manner similar to that in which gravestones are rotated.

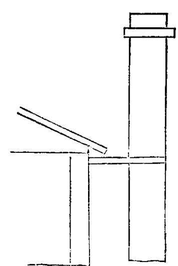

FIG. 25.

Mallet made observations similar to these in Italy. He tells us that a buttress may often not have time to transmit its stability to a wall. The wall and the buttress have different periods of vibration, and therefore they exert impulsive actions on each other. Effects like these were strikingly observable in many of the rural Italian churches where the belfry tower is built into one of the quoins of the main rectangular building.

Not only have we to consider the relative vibrations of the various parts of a building amongst themselves, but we have to consider the relation of the natural vibrations of any one of them or the vibration of the building as a whole, with regard to the earth, the vibrations of which it must be remembered are not strictly periodic.

Some of the more important results dependent upon the principle of "relative vibrational periods" may be understood from the following experiments:—

In fig. 26 A, B, and C are three flat springs made out of strips of bamboo, and loaded at the top with pieces of lead. At the bottom they are fixed into a piece of board D E, and the whole rests on a table F G. The legs of this table being slightly loose, by placing the fingers on the top of it, a quick short backward and forward movement can be produced. The weights on A and B are the same, but they are larger than the weight on C. Consequently the period of A and B are the same, but different to the period of C. The dimensions of these springs are as follows: height, 18 inches; A and B each carry weights equal to 320 grammes, and they make one vibration per second; C has a weight of 199 grammes, and makes 0.75 vibrations per second.

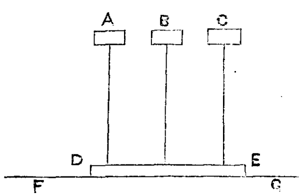

FIG. 26.

FIRST EXPERIMENT.—It will be be found that by giving the table a gentle backward and forward movement, the extent of which movement may be so small that it will be difficult to detect it with the eye, either A and B may be made to oscillate violently, whilst C remains still; or *vice versâ*, C may be caused to oscillate whilst A and B remain still. In the one case the period of shaking will have been synchronous with the natural period of A and B, whilst in the latter it will have been synchronous with that of C. This would seem to show us that if the natural period of vibration of a house, or of parts of it, at any time agree with the period of the shock, it may be readily thrown into a state of oscillation which will be dangerous for its safety.

SECOND EXPERIMENT.—Bind A and B together with a strip of paper pasted between them. (The paper used was three-eighths of an inch broad, and would carry a weight of nearly three pounds.) If the table be now shaken as before, A and B will always have similar movements, and tend to remain at the same distance apart, and as a consequence the strip of paper will not be broken. From this experiment it would seem that so long as the different portions of a building have almost the same periods of vibration, there will be little or no strain upon the tie-rods or whatever contrivance may be used in connecting the different parts.

THIRD EXPERIMENT.—Join A and C, or B and C with a strip of paper in a manner similar to the last experiment. If the table be now shaken with a period approximating either to that of A and B, or with that of C, the paper will be suddenly snapped.

This indicates that if we have different portions of a building of such heights and thicknesses that their natural periods of vibration are different, the strain upon the portions which connect such parts is enormous, and it would seem, as a consequence, that either the vibrators themselves, or else their connections must, of a necessity, give way. This was very forcibly illustrated in the Yokohama earthquake of February, 1880, by the knocking over of chimneys. The particular case of the chimneys is, however, better illustrated by the next experiment.

FOURTH EXPERIMENT.—Take a little block of wood three-quarters of an inch square and about one inch high, and place it on the top of A, B, or C. It will be found that, although the spring on which it stands is caused to swing backwards and forwards through a distance of three inches, the little block will retain its position.

This little block we may regard as the upper part of a chimney standing on a vibrating stack, and we see that, so long as this upper portion is light, it has no tendency to fall.

FIFTH EXPERIMENT.—Repeat the fourth experiment, having first placed a small leaden cap on the top of the block representing the chimney. (The cap used only weighed a few grammes.) When vibration commences it will be found that the block quickly falls. This would seem to indicate that chimneys with heavy tops are more likely to fall than light ones.

SIXTH EXPERIMENT.—Bind A and B together with a strip of paper and stand the little block upon the top of either. It will be found that the block will stand as in the fourth experiment.

SEVENTH EXPERIMENT.—Bind A and C, or B and C together, and place the block upon the top of either of them. When vibration commences although the paper may not be broken, the little block will quickly fall.

EIGHTH EXPERIMENT.—Take two pencils or pieces of glass tube and place them under the board D E. If the table F G be now shaken in the direction D E, it will be found that the springs will not vibrate.

In a similar manner if a house or portion of a house were carried on balls or rollers, as has already been suggested, it would seem that the house might be saved from much vibration.

NINTH EXPERIMENT.—Set any of the springs in violent vibration by gently shaking D E instead of the table, and then suddenly cease the actuating motion. It will be observed that at the moment of cessation the board and the springs will have a sudden and very decided motion of translation in the same direction as that in which the springs were last moving, and although the springs were at the time swinging through a considerable arc, all motion will suddenly cease.

This shows that if a house is in a state of vibration the strain at the foundations must be very great.

It would not be difficult to devise other experiments to illustrate other phenomena connected with the principle of relative vibrational periods, but these may perhaps be sufficient to show to those who have not considered this matter its great importance in the construction of buildings. Perhaps the greater portion of what is here said may be regarded as self-evident truisms hardly worth the trouble of demonstration. Their importance, however, seems to be so great that I hope that their discussion has not been altogether out of place.

I may remark that in the rebuilding of chimneys in Yokohama the principles here enunciated were taken advantage of by allowing the chimneys to pass freely through the roofs without coming in contact with any of the main timbers.

In putting up buildings to resist the effects of an earthquake, besides the idea of making everything strong because the earthquake is strong, there are several principles which, like the one just enunciated, might advantageously be followed but which as yet appear to have received but little attention.

TYPES OF BUILDINGS USED IN EARTHQUAKE COUNTRIES.—In Japan there are excellent opportunities of studying various types of buildings. The Japanese types, of course, form the majority of the buildings. The ordinary Japanese house consists of a light framework of posts of 4 or 5 inch scantling, built together without struts or braces, all the timbers crossing each other at right angles. The spaces are filled in with wattle-work of bamboo, and this is plastered over with mud. This construction stands on the top of a row of boulders or of square stones, driven into the surface soil to a distance varying from a few inches to a foot. The whole arrangement is so light that it is not an uncommon thing to see a large house rolled along from one position to another on wooden rollers. In buildings such as these, after a series of small earthquake shocks, we could hardly expect to find more fractures than in a wicker basket.

The larger buildings, such as temples and pagodas, are also constructed of timber. These are built up of such a multitude of pieces and framed together in such an intricate manner that they also are capable of yielding in all directions. The European buildings are, of course, made of brick and stone with mortar joints. Some of these, as the buildings of the Ginza in Tokio, are not designed for great strength. On the other hand, others have thick and massive walls and are equal in strength to those we find in Europe.

The third type of buildings are those which are built in blocks; and these blocks, being bound together with iron rods traversing the walls in various directions, are especially designed to withstand earthquakes. A system somewhat similar to this has been patented in America, and examples of these so-called earthquake-proof buildings are to be found in San Francisco.

Speaking of Japanese buildings, Mr. R. H. Brunton, who has devoted especial attention to them, says that,[1] "to imagine that slight buildings, such as are seen here (*i.e.* in Japan), are the best calculated to withstand an earthquake shock is an error of the most palpable kind." After describing the construction of a Japanese house in pretty much the same terms as we have used, he says "that with its unnecessarily heavy roof and weak framework it is a structure of all others the worst adapted to withstand a heavy shock." He tells us, further, that these views are sustained by the truest principles of mechanics. In order to render buildings to some extent proof against earthquakes, some of the heavy roofs in Tokio have been so constructed that they are capable of sliding on the walls. Mr. Brunton mentions a design for a house, the upper part of which is to rest on balls, which roll on inverted cups fixed on the lower part of the building, which is to be firmly embedded in the earth. A similar design was, at the suggestion of Mallet, used to support the tables carrying the apparatus of some of the lighthouses erected in Japan by Mr. Brunton. The very existence of these designs seems to in-

[1] See "Constructive Art in Japan," by R. H. Brunton, C.E., F.R.G.S., F.G.S., *Transactions of Asiatic Society of Japan*, December 22, 1873, and January 13, 1875.

dicate that the ordinary European house, however solidly and strongly it may be built, is not sufficient to meet the conditions imposed upon it. What is required is something that will give way—an approximation to the timber frame of a Japanese house, so strongly condemned by Mr. Brunton and others. The crucial test of the value of the Japanese structure, as compared with the modern buildings of brick and stone, is undoubtedly to be found by an appeal to the buildings themselves. So far as my own experience has gone, I must say that I have never seen any signs in the Japanese timber buildings which could be attributed to the effects of earthquakes, and His Excellency Yamao Yozo, Vice-Minister of Public Works, who has made the study of the buildings of Japan a speciality, told me that none of the temples and palaces, although many of them are several centuries old, and although they have been shaken by small earthquakes and also by many severe ones, show any signs of having suffered. The greatest damage wrought by large earthquakes appears to have resulted from the influx of large waves or from fires. In every case where an earthquake has been accompanied by great destruction, by consulting the books describing the same, it can be seen, from the illustrations in these books portraying confiragrations, that this destruction was chiefly due to fire. When we remember that nearly all Japanese houses are constructed of materials that are readily inflammable, it is not hard to imagine how destruction of this kind has come about. To a Japanese, living as he does in a house which has been compared to a tinder-box, fire is one of his greatest enemies, and in a city like Tokio it is not at all uncommon to see during the winter months many fires which sweep away from 100 to 500 houses. In one winter I was a spectator of three fires, each of which was said to have destroyed upwards of 10,000 houses. Of late years these fires have been considerably reduced.

Although it would appear that the smaller earthquakes of Japan produce no visible effect upon the native buildings, it is nevertheless probable that small effects may have been produced, the observation of which is rendered difficult by the nature of the structure. If we look at buildings of foreign construction, by which are meant buildings of brick and stone, the picture before us is quite different, and everywhere the effects of earthquakes are palpable even to the most casual observer. Of these effects numerous examples have already been given. Not only are these buildings damaged by the cracking of walls and the overturning of chimneys, but they also appear to be affected internally. For instance, in the timbers of the roof of the museum attached to the Imperial College of Engineering in Tokio, there are a number of diagonal pieces acting as struts or ties intended to prevent more or less horizontal movements taking place. Those which are rigidly joined together with bolts and angle irons have apparently suffered from their rigidity, being twisted and bent into various forms. The buildings in Tokio, which are strongly put together, being especially designed to withstand earthquakes, appear to have suffered but little. I know only one example which at the time of the severe shock of 1880 had several of its chimneys damaged.

The ordinary houses in Italy, though built of stone and mortar, are but poorly put together, and, as Mallet has remarked, are in no way adapted to withstand the frightful shakings to which they are subjected from time to time.

In the large towns, like Naples, Rome, and Florence, where happily earthquakes are of rare occurrence, although the building may be better than those found in the country, the height of the houses and the narrowness of the streets are sufficient to create a shudder, when we think of the possibly of the occurrence of a moderately severe earthquake.

In South America, although many buildings are built with brick and stone, the ordinary houses, and even the larger edifices, are specially built to withstand earthquakes. In Mr. James Douglas's account of a "Journey Along the West Coast of South America," we read the following[2]: "The charac-

[2] *Journal of the American Geographical Society*, vol. x.

teristic building material of Guayaquil is bamboo, which grows to many inches in thickness, and which, when cut partially through longitudinally at distances of an inch or so, and once quite through, can be opened out into fine elastic boards of serviceable width. Houses, and even churches, of a certain primitive beauty are built of such reeds, so bound together with cords that few nails enter into the constructions, and which, therefore, yield so readily to the contortions of the earth during an earthquake as to be comparatively safe."

Here we have a house, which, so far as earthquakes are concerned, is an exaggerated example of the principles which are followed in the construction of an ordinary Japanese dwelling.

Another plan adopted in South America can be gathered from the same author's writings upon Lima, about which he says: "To build high houses would be to erect structures for the first earthquake to make sport of, and therefore, in order to obtain space, safety, and comfort, the houses of the wealthy surround court after court, filled with flowers, and cooled with fountains, connected one with another with wide passages which give a vista from garden to garden."

History would indicate that houses of this type have been arrived at as the results of experience, for it is said that when the inhabitants of South America first saw the Spaniards building tall houses, they told them they were building their own sepulchres.[3]

In Jamaica, we find that even as early as 1692 experience had taught the Spaniards to construct low houses, which withstood shakings better than the tall ones.[4]

Typical Houses for Earthquake Countries.—From what has now been said about the different buildings found in earthquake countries, it will be seen that if we wish to put up a building able to withstand a severe shaking, we have before us structures of two types. One of these types, may be com-

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[3] *Phil. Trans.*, li, 1760. [4] *Ibid.*, xviii.

pared with a steel box, which even were it rolled down a high mountain, would suffer but little damage; and the other, with a wicker basket, which would equally withstand so severe a test. Both of these types may be, to some extent, protected by placing them upon a loose foundation, so that but little momentum enters them at their base. One suggestion is to place a building upon iron balls. Another method would be to place them upon two sets of rollers, one set resting upon the other set at right angles. The Japanese, we have seen, place their houses on round stones. The solid type of building is expensive, and can only be approached partially, whilst the latter is cheap, and can be approached closely. In the case of a solid building it would be a more difficult matter to support it upon a movable foundation than in the case of a light framework. Such a building is usually firmly fixed on the ground, and consequently at the time of an earthquake, as has already been shown by experiment, must be subjected to stresses which are very great. In consequence also of the greater weight of the solid structure, more momentum will enter it at its base than in the case of the light structure. Also, we must remember that the rigidity favours the transmission of momentum, and with rigid walls we are likely to have ornaments, coping-stones, and the comparatively freer portions forming the upper part of a building displaced; whilst, with flexible walls absorbing momentum in the friction of their various parts, such disturbances would not be so likely. Mr. T. Ronaldson, referring to this, says that in 1868, at San Francsco, the ornamental stone-work in stone and cement buildings was thrown from its position, whilst similar ornaments in neighbouring brick buildings stood. To reduce the top weight of a building, hollow bricks might be employed. To render a building more homogeneous and elastic, the thickness of bricks might be reduced. Inasmuch as the elasticity of brick and timber are so different, the two ought to be employed separately. For internal decorations plaster mouldings might be replaced by *papier mâché* and *carton-pierre*, the elastic yielding of which is comparatively great.[5] Houses, whether of brick and stone, or of timber, ought to be broad and low, and the streets three or four times as wide as the houses. The flatter the roofs the better.

One of the safest houses for an earthquake country would probably be a one-storied strongly framed timber house, with a light flattish roof made of shingles or sheet-iron, the whole resting on a quantity of small cast-iron balls carried on flat plates bedded in the foundations. The chimneys might be made of sheet-iron carried through holes free of the roof. The ornamentation ought to be of light materials.

At the time of severe earthquakes many persons seek refuge from their houses by leaving them. In this case accidents frequently happen from the falling of bricks and tiles. Others rush to the doorways and stand beneath the lintels. Persons with whom the author has conversed have suggested that strongly constructed tables and bedsteads in their rooms would give protection. To see persons darting beneath tables and bedsteads would undoubtedly give rise to humiliating and ludicrous exhibitions. This latter idea is not without a value, and most certainly, if applied in houses of the type described, would be valuable.

The great danger of fire may partially be obviated by the use of "earthquake lamps," which are so constructed that before they overturn they are extinguished. It is said that in South America some of the inhabitants are ready at any moment to seek refuge in the streets, and they have coats prepared, stocked with provisions and other necessaries, which, if occasion demands, will enable them to spend the night in the open air. These coats, called "earthquake coats," might also, with properly constructed houses, be rendered unnecessary.

DESTRUCTION DUE TO THE NATURE OF THE UNDERLYING ROCKS.—That the nature of the ground on which a building

[5] T. Ronaldson, *A Treatise on Earthquake Dangers, &c.*

stands is intimately related with the severity of the blow it receives is a fact which has often been demonstrated.

One cause of destruction is due to placing a building on foundations which are capable of receiving the full effects of a shock, and transmitting it to be buildings standing on them,

For instance, the reason why a soft bed might possibly make a good foundation, is, as has been pointed out by Messrs. Perry and Ayrton, because the time of transmission of momentum is increased; in fact, the soft bed is very like a piece of wood interposed between a nail and the blows of a hammer—it lengthens the duration of impact. For this reason we are told that a quaking bog will make a good foundation. When a shock enters loose materials its waves will be more crowded, and it is possible that a line of buildings may rest on more than one wave during a shock. There are many examples on record of the stablity of buildings which rested on beds of particular material at the time of destructive earthquakes. As the observations which have been made by various writers on this object appear to point in a contrary direction, I give the following examples:—

In the great Jamaica earthquake of 1692, the portions of Port Royal which remained standing were situated on a compact limestone foundation; whilst those on sand and gravel were destroyed ("Geological Observer," p. 426). Again, on p. 148 of the same work, we read:—"According to the observations made at Lisbon, in 1737, by Mr. Sharpe, the destroying effects of this earthquake were confined to the tertiary strata, and were most violent on the blue clay, on which the lower part of the city is constructed. Not a building on the secondary limestone or on the basalt was injured."

In the great earthquakes of Messina, those portions of the town situated on alluvium, near the sea, were destroyed, whilst the high parts of the town, on granite, did not suffer so much. Similar observations were made in Calabria, when districts consisting of gravel, sand, and clay become, by the shaking, almost unrecognisable, whilst the surrounding hills of slate and granite were but little altered. At San Francisco, in 1868, the chief destruction was in the alluvium and made ground.

At Talacahuano, in 1835, the only houses which escaped were the buildings standing on rocky ground; all those resting on sandy soil were destroyed.

From the results of observations like these, it would seem the harder rocks form better foundations than the softer ones. The explanation of this, in many cases, appears to lie in the fact that the soft strata were in a state of unstable equilibrium, and by shaking, they were either caused to settle or swing back and forth like a mass of jelly. Observations like the following, however, point out another reason why soft strata may sometimes afford a bad foundation.

"Humboldt observed that the Cordilleras, composed of gneiss and mica-slate, and the country immediately at their foot, were more shaken than the plains."[6]

"Some writers have asserted that the wave-like movements (of the Calabrian earthquake in 1783) which were propagated through recent strata from west to east, became very violent when they reached the point of junction with the granite, as if a reaction was produced when the undulatory movement of the soft strata was suddenly arrested by the more solid rocks."

Dolomieu when speaking of this earthquake says, the usua effect "was to disconnect from the sides of the Apennines all those masses (of sand and clay) which either had not sufficient bases for their bulk, or which were supported only by lateral adherence."

These intensified actions taking place at and near to lines of junction between dissimilar strata are probably due to the phenomena of reflection and refraction.

When referring to the question as to whether buildings situated on loose materials suffered more or less than those on

[6] *Principles of Geology,* Lyell, vol. ii. p. 106.

solid rocks, Mallet, in his description of the Neapolitan earthquake of 1857, remarks :—"We have in this earthquake, towns such as Saponara and Viggiano, situated upon solid limestone, totally prostrated ; and we have others such as Montemarro, to a great extent based upon loose clays, totally levelled. We have examples of almost complete immunity in places on plains of deep clay as that of Viscolione, and in places on solid limestone, like Castelluccio, or perched on mountain tops like Petina."[7]

After reading the above, we see that the probable reason why, in several cases, beds of soft materials have not made good foundations, consists in the fact that they have either been of small extent or else have been observed only in the neighbourhood of lines which divided them from other formations, which lines are always those of great disturbances.

At the end of his description of the Neapolitan earthquake of 1857, Mallet says that more buildings were destroyed on the rock than on the loose clay. This, however, he remarks, is hardly a fact from which we can draw any valuable deductions, because it so happened that more buildings were constructed on the hills than on the loose ground.

Professor D. S. Martin, writing on the earthquake of New England in 1874, remarks that in Long Island the shock was felt where there was gneiss between the drift. Around portions to the east the observations were few and far between. He also remarks that generally the shocks were felt more strongly and frequently on rocky than on soft ground.[8]

From these examples, it would appear that the hard ground, which usually means the hills, forms a better foundation than the softer ground, which is usually to be found in the valleys and plains. Other examples, however, point to a different conclusion. For instance, a civil engineer, writing about the

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[7] *The Neapolitan Earthquake of* 1857, R. Mallet, vol. ii. p. 359.

[8] *Am. J. Sci.* x. 191.

New Zealand earthquake of 1855, when all the brick buildings in Wellington were overthrown, says that "it was most violent on the sides of the hills at those places, and least so in the centre of the alluvial plains."[9]

In this example it must be noticed that the soft alluvium here referred to was of large extent, and not loose material resting on the flanks of rocks, from which it was likely to be shaken down, as in most of the previous examples.

The results of my own observations on this subject point as much in one direction as in the other. In Tokio, from instrumental observations upon the slopes and tops of hills, the disturbance appears to be very much less than it is in the plains. Thus, at my house, situated on the slope of a hill about 100 feet in height, for the earthquake of March 11th, 1882, I obtained a maximum amplitude of motion of from three to four millimètres only, whilst Professor Ewing, with a similar instrument, situated on the level ground at about a mile distant, found a motion of fully seven millimètres. This calculation has been confirmed by observations on other earthquakes. Thus, for instance, in the destructive earthquake of 1855, when a large portion of Tokio was devastated, it was a fact, remarked by many, that the disturbance was most severe on the low ground and in the valleys, whilst on the hills the shock had been comparatively weak. As another illustration, I may mention that within three-quarters of a mile from my house in Tokio there is a piece of ground which has so great a reputation for the severity of the shakings it receives that I am told its marketable value has been considerably depreciated, and it is now untenanted.

In Hakodate, which is a town situated very similarly to Gibraltar, partly built on the slope of a high rocky mountain and partly on a level plain, from which the mountain rises, the rule is similar to that for Tokio, namely, that the low, flat ground is shaken more severely than the high ground. At

[9] *Reports of British Association*, 1858, p. 106.

Yokohama, sixten miles south-west from Tokio, the rule is reversed, as was very clearly demonstrated by the earthquake of February, 1880, when almost every house upon the high ground lost its chimney, whilst on the low ground there was scarcely any damage done; the only places on the low ground which suffered were those near to the base of the hills. The evidence as to the relative value of hard ground as compared with soft ground, for the foundation of a building, is very conflicting. Sometimes the hard ground has proved the better foundation and sometimes the softer, and the superiority of one over the other depends, no doubt, upon a variety of local circumstances.

These latter observations open up the inquiry as to the extent to which the intensity of an earthquake may be modified by the topography of the disturbed area.

THE SWING OF MOUNTAINS.—If an earthquake wave is passing through ground the surface of which is level, so long as this ground is homogeneous, as the wave travels further and further we should expect its energy to become less and less, until, finally, it would insensibly die out. If, however, we have standing upon this plain a mountain, judging from Mallet's remarks, this mountain would be set in a state of vibration much in the same way as a house is set in vibration, and it would tend to oscillate backward and forward with a period of vibration dependent upon the nature of its materials, size, and form. The upper portion of this mountain would, in consequence, swing through a greater arc than the lower portion, and buildings situated on the top of it would swing to and fro through a greater arc than those which were situated near its foot. This explanation why buildings situated on the top of a mountain should suffer more than those situated on a plain, is one which was offered by Mallet when writing of the Neapolitan earthquake. He tells us that towns on hills are "rocked as on the top of masts," and if we accept this explanation it would, in fact, be one reason why the houses situated on the Bluff at

Yokohama suffered more than those situated in the Settlement. This explanation is given on account of the great authority it claims as a consequence of its source. It is not clear how the statement can be supported, as different portions of the mountain receive momentum in opposite directions at the same time.

WANT OF SUPPORT ON THE FACES OF HILLS.—When a wave of elastic compression is propagated through a medium, we see that the energy of motion is being continually transmitted from particle to particle of that medium. A particle, in moving forwards, meets with an elastic resistance of the particles towards which it moves, but, overcoming these resistances, it causes these latter particles to move, and in turn to transmit the energy to others further on. So long as the medium in which this transfer of energy is continuous, each particle has a limit to its extent of motion, dependent on the nature of the medium. When, however, the medium, which we will suppose to be the earth, is not continuous, but suddenly terminates with a cliff or scarp, the particles adjacent to this cliff or scarp, having no resistance offered to their forward motion, are shot forward, and, consequently, the ground here is subjected to more extensive vibrations than at those places where it was continuous. This may be illustrated by a row of marbles lying in a horizontal groove; a single marble rolled against one end of this row will give a concussion which will run through the chain, like the bumping of an engine against a row of railway cars, and as a result, the marble at the opposite end of the row, being without support, will fly off. Tyndall illustrates the same thing with his well known row of boys, each one standing with his arms stretched out and his hands resting upon the shoulders of the boy before him. A push being give to the boy at the back, the effect is to transmit a push to the first boy, who, being unsupported, flies forward.

In the case of some earthquakes, most disastrous results have occurred which seem only to admit of an explanation such as this. A remarkable instance of this kind occurred when the great earthquake of 1857 "swept along the Alps from Geneva to the east-north-east, and its crest reached the edge of the deep glen between Zermatt and Visp. Then the upper part of the wave-movement, a thousand or two thousand feet in depth from the surface, came to an end; the forward pulsation acted like the breaker of the sea, and heavy falls of rock encumbered the western side of the valley."

Earthquake Shadows.—If a mountain stands upon a plain through which an elastic wave is passing, which is almost horizontal, the mountain is, so to speak, in the *shadow* of such a wave. If we only consider the normal motion of this wave, we see that the only motion which the mountain can obtain will be a wave of elastic distortion produced by a shearing force along the plain of the base. Should, however, the wave approach the mountain from below, and emerge into it at a certain angle, only the portion of the mountain on the side from which the wave advanced could remain in shadow, whilst the portion on the opposite side would be thrown into a state of compression and extension. Portions in shadow, however, would be subject to waves of elastic distortion. In a manner similar to this we may imagine that certain portions of the Bluff, so far as the advancing wave was concerned, were in shadow, and thus saved from the immediate influence of the direct shock. The situation which might be in the shadow of one shock, however, it is quite possible might not be in that of another. We must also remember that a place in shadow for a direct shock might be affected by reflected waves, and also by the transverse vibrations of the direct shock. These effects are over and above the effects produced by the waves of elastic distortion just referred to. It might be asked whether whole countries, like England, which are but seldom shaken, are in shadow.

Destruction due to the interference of Waves.—Referring to the section of the ground at Yokohama (see Fig. 27, Milne's "Earthquakes," p. 138), it will be seen that both the

Settlement and the Bluff stand upon beds of gravel capping horizontal beds of grey tuff. The gravel of that portion of the Settlement on the seaboard originally formed the line of a shingle beach. That portion of the Settlement back from the sea stands upon ground which was originally marshy. In the central portion of the Settlement this bed of gravel is very thick, perhaps 100 feet or so, but as you near the edge of the Bluff it probably becomes thinner, until it finally dies out upon the flanks of the scarps.

On the top of the Bluff, the beds of gravel will, in every probability, be generally thinner than they are upon the lower level. The beds of tuff, which is a soft, grey-coloured clay-like rock, produced by the solidification of volcanic mud, appear, when walking on the seaboard, to be horizontally stratified. If there is a dip inland, it is in all probability very slight. Here and there the beds are slightly faulted. Taken as a whole, we may consider these beds as being tolerably homogeneous, and an earthquake in passing through them would meet with but little reflection or refraction. At the junction of these beds with the overlying gravels, both reflection and refraction would comparatively be very great.

On entering the gravel, as the wave would be passing into a less elastic medium, the direction of the wave would be bent towards the perpendicular to the line of junction, and the angle of emergence at the surface would consequently be augmented. At the surface certain reflection would also take place, but the chief reflections would be those at the junction of the tuff and the alluvium.

Under the Settlement it is probable that all the reflections which took place would be single. If the lines drawn representing wave fronts are districts of compression, then, where two of the lines cross each other, there would be double energy in producing compression. Similarly, districts of rarefaction might accord, and, again, compression of one wave might meet with the rarefaction of another and a neutralisation of effect take place. A diagram illustrating concurrence and interference of this description is given in Le Conte's "Elements of Geology," p. 115. The interference which has been spoken of, however, is not the greatest which would occur. The greatest would probably be beneath the Bluff and the scarps which run down to join the level ground below. This would be the case because it is a probability that there might not only be cases of interference of single reflected waves, but also of waves which had been not only twice but perhaps thrice reflected. The number of districts where there would be concurrence and interference would, in consequence of the number of times waves might be reflected, be augmented. Here the violence of the shock would, at certain points, be considerably increased, but as a general result energy must be lost, so that even if some of the reflected waves found their way into the portion we have regarded as being in shadow, their intensity would not be so great as if they had entered it directly.

The shaking down of loose materials from the sides of hills may be partially explained on the assumption of an increased disturbance due to interference.

EARTHQUAKE BRIDGES.—In certain parts of South America there appear to exist tracts of ground which are practically exempt from earthquake shocks, whilst the whole country around is sometimes violently shaken. It would seem as if the shock passes beneath such a district as water passes beneath a bridge, and for this reason these districts have been christened "bridges."

This phenomenon appears to depend upon the nature of the underlying soil. When an elastic wave passes from one bed of rock to another of a different character, a certain portion of the wave is reflected, while the remainder of it is transmitted and refracted, and "bridges" we may conceive of as occurring where the phenomenon of total reflection occurs.

In the instances given of soft materials having proved good foundations, it was assumed that they had chiefly acted as absorbers of momentum. They have also acted as reflecting surfaces, and where no effects have been felt by those residing on them, this may have been the result of total reflection, and the soft beds thus have played the part of "bridges."

Fuchs gives an example taken from the records of the Syrian earthquake of 1837, where not only neighbouring villages suffered differently, but even neighbouring houses. In one case a house was entirely destroyed, whilst in the next house nothing was felt.

In Japan, at a place called Choshi, about 55 miles east of the capital, it is said that earthquakes are but seldom felt, although the surrounding districts may be severely shaken.

From descriptions of this place it would appear that there is a large bassaltic boss rising in the midst of alluvial strata. The immunity from earthquakes in this district has probably given rise to the myth of the Kanami Rock, which is a stone supposed to rest upon the head of a monstrous catfish (*Namazu*), which by its writhings causes the shakings so often felt in this part of the world.[10]

Prof. D. S. Martin, writing on the earthquake of New England in 1874, says that it was felt at four points; it was felt in the heart of Brooklyn all within a circle of half a mile across; "and this fact would suggest that a ridge of rock perhaps approaches the surface at that point, though none is known to appear."[11]

The subject of special districts, which are more or less protected from severe shakings, will be again referred to, and it will be seen that after a seismic survey has been made even of a country like Japan, where there are on the average at least two earthquakes per day, it is possible to choose a place to build in as free from earthquakes as Great Britain.

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[10] See chapter "Causes of Earthquakes" for details of this myth.
[11] *Am. Jou. Sci.* vol. x. p. 191.

General Examples of Earthquake Effects.—The following examples of earthquake effects are drawn from Mallet's account of the Neapolitan earthquake of 1857.

At a town called Polla there was great destruction. Judging from the fissures in the parts that remained standing it seemed that the emergence of the shock had been more vertical in the upper part of the town than in the lower, proving that whatever had been the angle below, the hill had itself vibrated, which, being horizontal, had modified the angle of the fissures.

Diano suffered but little, partly because it was well built, and partly on account of its situation, which was such that before the shock reached it the disturbance had to pass from beds of clay into nearly vertically placed beds of limestone. Also a great portion of the shock was cut off by the Vallone del Raccio to the north and north-west of the town. Here the effects of the partial extinction of the wave on the "free outlaying stratum" were visible in the masses of projected rock.

Castellucio did not suffer because its well buttressed knoll was end on to the direction of the shock, and on account of a barrier of vertical breccia beds protecting it upon the east.

Pertosa stands on a mound. The destruction was least in the southern part of the town. From the relation of the beds of breccia on which the town stands, and the direction of the wave path, it is evident that the southern part of the town received the force of the shock through a greater thickness of the breccia beds than the other parts did.

Petina, standing on a level limestone spur jutting out from a mountain slope, suffered nothing, whilst Anletta five miles to the south-west, and Pertosa six miles distant, were in great part prostrated. (1) The terrace did not vibrate, and (2) between Petina and Anletta there is almost 6,000 feet of piled up limestone, so that any shock emergent at a steep angle had to pass up transversely through these beds.

Protection of Buildings.—In addition to giving proper construction to our buildings, choosing proper foundations and positions for them, something might possibly be done to ward off the destructive effects of an earthquake. We read that the Temple of Diana at Ephesus was built on the edge of a marsh, in order to ward off the effect of earthquakes. Pliny tells us that the Capitol of Rome was saved by the Catacombs, and Elisée Reclus[12] says that the Romans and Hellenes found out that caverns, wells, and quarries retarded the disturbance of the earth, and protected edifices in their neighbourhood. The tower of Capua was saved by its numerous wells. Vivenzis asserts that in building the Capitol the Romans sunk wells to weaken the effects of terrestrial oscillations. Hunboldt relates the same of the inhabitants of San Domingo.

Quito is said to receive protection from the numerous cañons in the neighbourhood, whilst Lactacunga, fifteen miles distant, has often been destroyed.

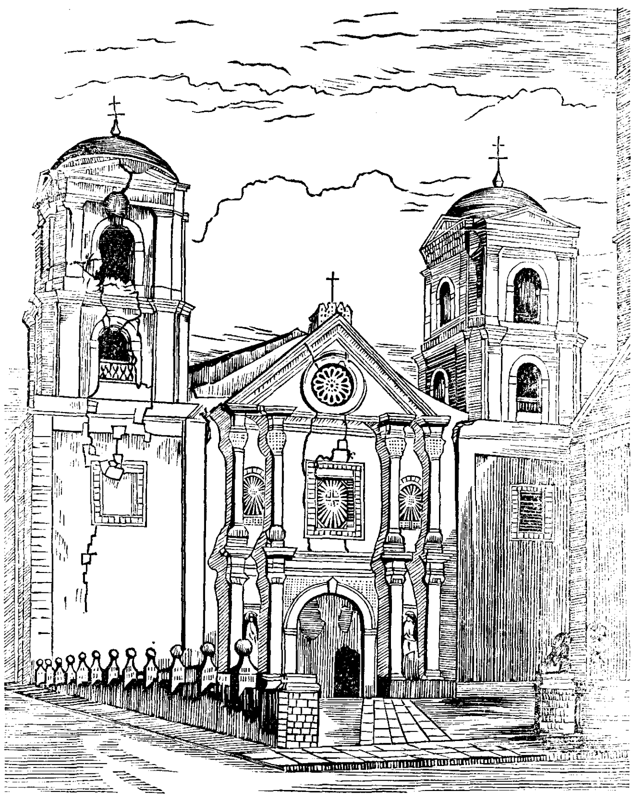
Similarly, it is extremely probable that many portions of Tokio have from time to time been protected more or less from the severe shocks of earthquakes by the numerous moats and deep canals which intersect it.

Although we are not prepared to say how far artificial openings of this descriptiou are effectual in warding off the shocks of earthquakes, from theoretical considerations, and from the fact that their use has been discovered by persons who, in all probability, were without the means of making theoretical deductions, the suggestions which they offer are worthy of attention.

Effects due to bad Construction.—In order that minimum destruction should be produced in a building by an earthquake, from what has already been said it is evident that certain principles other than these which are usually followed ought to be adopted. Much, however, may be done by con-

[12] *The Earth,* p. 199.

struction of an ordinary kind providing that the same be good. In confirmation of this we have only to refer to the accounts of almost any destructive earthquake when we at once see that the buildings which have suffered the most have been these which have been badly constructed. Referring to Mallet's



account of the Neapolitan earthquake, we read that the Military road of Campostrina which winds round valley gorges, crosses one of these by a well built viaduct. At this place although the street emerged at a steep angle and transverse to the length of the viaduct, the same suffered no damage.

At Atena, which stands upon the crest of a spur of absolutely bare rock, the destruction was very great. Amidst the ruin, however, the tower of a church 90 feet in height and 22 feet square at the base stood uninjured. The walls are 3′ 8″ thick at the bottom and 12″ at the summit, they are well built and tied together with chain bars. High up above the town there were several well built houses which did not suffer. Another, among the many other instances which might be quoted, occurred at the magnificent monastery of Certosa de S. Lorenza, which was almost entirely reduced fo ruin. Almost the only portion which escaped was an elliptic staircase said to have been built by Michael Angelo, and this was probably owing to the careful nature of the workmanship. Effects like these, resultant on bad building, Mallet speaks about at considerable length. The destruction which occurred in 1869 in San Francisco was chiefly attributed to the use of bad mortar. If a building is high even good construction may not save it. The tower of the Cathedral at Manila was so shattered that it subsequently fell. The thickness of the walls and the size of the blocks which were disloged without breaking up into fragments certainly testify to its solidity and the adherence of its parts (see illustration, p. 81).

General Conclusions.—The following are a few of the more important results which may be drawn from the preceding chapter :—

1. In choosing a site for a house find out by the experience of others or experimental investigation the localities which are least disturbed. In some cases this will be upon the hills, in others in the valleys and on the plains.

2. Avoid loose materials resting on harder strata.

3. If the shakings are definite in direction, place the blank walls parallel to such directions, and the walls with many openings in them at right angles to such directions.

4. Avoid the edges of scarps or bluffs, both above and below.

5. So arrange the openings in a wall, that for horizontal

stresses the wall shall be of equal strength for all sections at right angles.

6. Place lintels over flat arches of brick or stone.

7. To withstand destructive shocks either rigidly follow one or other of the two systems of constructing an earthquake-proof building. The light building on loose foundations is the cheaper and probably the better.

8. Let all portions of a building have their natural periods of vibration nearly equal.

9. If it is a necessity that one portion of a building should have a very different period of vibration to the remainder, as for instance a brick chimney in a wooden house, it would seem advisable either to let these two portions be sufficiently free to have an independent motion, or else they must be bound together with great strength.

10. Avoid heavy topped roofs and chimneys. If the foundations were free the roof might be heavy.

11. In brick or stone work use good cement.

12. Let archways curve into their abutments.

13. Let roofs have a low pitch, and the tiles, especially those upon the ridges, be well secured.