California Institute of Technology
Pasadena, California

Contribution No. 4

Earthquakes and their Habits in California*

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A CERTAIN reluctance in earlier years to discuss earthquakes publicly in California has given way in large measure to the conviction that the best way to combat an alleged evil is to know all about it and to be prepared for it.

Earthquakes are of course vibrations of the ground. The movement is complicated in nature. The ground at a given place may move horizontally back and forth, or vertically up and down, or oscillate in any oblique direction between the two, and the direction of movement may change suddenly. Moreover, the ground may tilt first in one direction, and then immediately in another, as surface earthquake waves pass underneath the spot. Appalling as these motions are to the senses, they are in reality but small movements of the ground. The backward and forward motion is probably never more than a few inches, except in alluvial filled areas where it may perhaps attain several feet, and in the great majority of rather severe earthquakes the solid ground or rock appears to have oscillated less than an inch. But in such shocks the vibration is repeated many times, continuing sometimes for a minute or two, and the force is irresistably great; buildings may begin to sway more and more violently and finally rack to pieces, and the phenomenon may become quite terrifying.

The period of vibration, that is the time required for a particle to move away from a point and return to it, is in violent earthquakes usually between one-quarter second and two seconds; commonly the vibrations are at about the rate of one hundred per minute. Hence the movements may be said to be in general small but rapid.

Earthquakes are caused in several different ways. Occasionally the roof of an underground cavern collapses, and the blow struck by the falling mass on the floor of the cavern may shake the surrounding territory somewhat. Great landslides similarly disturb adjoining areas to some degree. Lava, forcing its way upward through the solid rock or bursting forth from the side of a newly-made fissure on the flanks of a volcano, sets up vibrations of very considerable intensity at times. The explosion of a volcano, caused usually by the plugging of its throat by cooled lava and its final expulsion by the accumulated pressures below, results sometimes in the partial demolition of the peak and the severe shaking of the immediately surrounding country. But while perhaps the majority of persons think that earthquakes are normally associated with volcanic activity, the greater part of all shocks, and particularly the more severe quakes and those which affect large areas vigorously, are caused by slipping along fractures or breaks in the crust of the earth known as faults. Faults separate great blocks of the crust which move with respect to each other, vertically or horizontally or obliquely. Faults go down into the body of the earth perhaps forty miles, but probably not much deeper; the rocks at greater depths are believed to be, not liquid, but nevertheless in a condition such that they do not deform by breaking but by a peculiar type of solid flow.

Certain forces tend to shift the fault blocks. These are generated perhaps by contraction of the earth or possibly by movement of interior rock bodies which may tend to drag overlying parts of the crust along much as the cooled surface of a lava flow is carried forward if the interior parts continue to move. The central parts of the blocks probably move past each other with slow but constant rate, but the friction on the fault plane is so great that slipping is not continuous but intermittent. Between times of slipping the margins of the fault blocks are bent back as the centers of the blocks move past each other, so that a straight fence built across the fault line would be gradually bent for perhaps a mile or two on each side of the fault. When the accumulated stress is sufficient to overcome the friction on the fault, a slip occurs, and the fence would be broken into two sections, both approximately straight again, through the springing back of the margins of the blocks into a position of no strain. This is usually referred to as the elastic rebound theory of earthquakes. The slipping along the fault line may take a minute or two, if the displacement is large, and the earthquake in the surrounding country is believed to be caused by the grating of the rough walls on the two sides of the fault as they rub past each other. This grating is thought to set up the vibrations which in severe earthquakes cause a quivering of the whole globe.

The displacement on the fault may be twenty feet or more, as it was in some localities in the 1906 San Francisco earthquake. It is the small vibrations, however, which radiate outward in every direction from the fault that constitute the earthquake, and not the large displacement along the fault, which seems to be limited to a narrow strip along the fault line. And it should be pointed out that earthquakes so far studied have not originated from new breaking of the rocks, but from renewed movement along fault lines which have probably been in existence for millions of years and along which repeated slipping has occurred causing earthquakes perhaps hundreds or thousands of times before. Of course the first breaking along a fault doubtless caused a shock also.

Each earthquake sends out in all directions three different kinds of waves. The exact nature of each kind need not be discussed here, but the important facts are that these three kinds travel at different velocities through the body of the earth and that each kind can usually be recognized on the seismographic record of an earthquake. The first type of wave to arrive travels at perhaps four miles a second; the second type two and one-half miles per second. The third type travels more slowly still. The seismologist can determine from his record the interval of time which elapsed between the arrival of the first and second types of waves, and knowing the velocities of these types from many other observations, he can easily compute the distance of the earthquake from the seismographic station where the record was made. The distance is obviously roughly proportional to the time interval between the arrival of the two sets of waves. Knowing the distance of the earthquake from two seismographic stations he can draw on a map a circle around each station with a radius equal to the computed distance of the earthquake from that station and the earthquake will have occurred at one of the two points of intersection of the two circles. Usually reports from the stricken area will indicate which of the two computed locations is the correct one, but if the seismologist has a distance determination from a third station, the circle drawn around that station will of course determine the location of the center of the quake at the single point of intersection of the three circles.

There is no mystery about the operation of the earthquake recording instruments known as seismographs. These devices, many in number of types, aim to measure the movement of the ground relative to a mass or weight which is suspended in a manner such that it remains practically

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fixed or stationary during the earthquake. A homely illustration of the principle involved would be a child sitting in a swing with its toe lightly touching the sand below. An earthquake might shift the ground sidewise and the tree as well, but the child, suspended in the swing, would because of its inertia remain nearly stationary and its toe would trace on the sand a pattern approximating the path which any point on the ground followed during the earthquake.

In the older types of seismographs a steady weight corresponding to the child but weighing anywhere from a few pounds to a ton or more is suspended, usually from a rigid metal standard firmly attached to a concrete pier which is set well into the ground. On the same pier is a rotating drum carrying smoked paper on which a needle connected to the steady weight traces a line. In an earthquake the ground, pier, standard, and drum all move, but the suspended weight tends to remain stationary, and the movement of the drum past the weight is traced by the needle, the oscillations usually being magnified several score times in size by some mechanical arrangement. One instrument registers the north-south, and another the east-west component of the motion, and a third, of somewhat different construction, records the vertical motion, so that the path of any ground particle can be ascertained in three-dimensional space.

Dr. Wood and Dr. Anderson of the Carnegie Institution of Washington have recently perfected a new compact type of seismometer which, without the recording apparatus, is smaller in size than an ordinary microscope. In this device a small weight is attached to a tightly stretched vertical wire around which the earthquake causes the weight to rotate slightly. A small mirror attached to the weight reflects a strong beam of light on moving photographic paper and swinging of the weight and mirror of course causes the beam to waver and produce a waving line on the paper corresponding to the movement of the ground in the earthquake. It is planned to install several of these instruments at judiciously chosen points in California with the hope of gaining from the records much valuable information regarding the nature of the shocks, including some data from which calculations may be made regarding the strains to which buildings may expectably be subjected during rather strong shocks.

As is so often the case in scientific investigations, the results may throw light on far more important questions than those which it was the original purpose of the investigation to answer. While seismology has told us much about earthquakes it is a striking fact that we have gained more knowledge regarding the state of the interior of the earth from observations on distant earthquakes than from any other source. The nature of the waves which come to us through the deep interior from earthquakes on the other side of the globe, and the rates at which the waves travel, indicate to us that the interior is not a fluid mass but is more rigid than steel. Volcanic lavas probably exude merely from pockets or abscesses in the rigid frame.

The geologist is often asked: how do you know where the faults are and how do you recognize them? These great breaks in the crust are usually indicated quite clearly on the surface of the land. The movement on a fault has commonly brought two different kinds of rocks or formations together or in contact at the fault line. The stratification on the two sides of the fault is usually inclined differently, for the movement of one block with reference to the other has usually given it a different tilt; a sudden change in dip or inclination of the rock therefore helps the geologist to locate a fault in the field. Polished rock surfaces, due to the slipping of the rocks on each other, and ground up rock, pulverized by the movement and pressure, likewise give evidence of the position of the fault. And where it crosses hills, a gulch or depression is likely to follow the line of the fault, for the crushed rock along the fracture is eroded down more rapidly than the solid rock on the two sides. Springs abound along faults. And if movement on the fracture has been recent, ponds and small lakes mark its course across the country, for slices of the adjacent blocks break off during the movements on the fault, and sinking down, create depressions in which the drainage water gathers. The fault is usually not a single line, however, but more commonly a crushed zone many feet, and often tens or hundreds of feet in width. On renewed movement breaking may occur anywhere within this zone.

Many of the principal faults in central and southern California have been mapped and are shown on a fault map recently published by the Seismological Society of America. (It can be purchased from the Secretary of the Society, who can be addressed at Stanford University, California.) The Coast Ranges of California are broken up into a series of north-south blocks, so that one crosses several faults and the intervening fault blocks in going from the ocean to the interior valley. Of these great breaks in the crust the San Andreas fault is perhaps the best known. Commencing some miles off shore near the Oregon-California line, it crosses points of land at two or three localities north of the Golden Gate and passing along the ocean bottom just outside the Gate, it strikes inland about ten miles south of San Francisco. It passes near Palo Alto, San Jose, Hollister, and traversing the Carriso Plains, Tejon, Cajon, and Gorgonio Passes, it extends down the Salton Sink depression and presumably into the Gulf of California. It may continue across southern Mexico into the earthquake region of the Carribean. It is one of the major structural features of the earth. A number of intense earthquakes have resulted from slipping on some part of this fault. The 1906 San Francisco earthquake had its origin in a displacement along 190 miles of its length, the largest offset or slip being about 21 feet west of Mt. Tamalpais. This line has undergone movements for many millions of years, doubtless giving earthquakes intermittently for all that time, and it is scarcely to be supposed that its restlessness is done. Doubtless, with more or less constantly accumulating stresses along this line, it has a certain rough periodicity of movement, but we have only the roughest notion as yet as to the interval between shocks. Experience from several shocks would be necessary to gain a definite idea; but moreover the interval probably is itself changeable to some degree.

A humorous aspect of the San Andreas fault is that San Franciso lies just east of it and Los Angeles somewhat to the west of it. The west side is moving northward, and should displacements of 21 feet, as occurred in 1906, continue indefinitely, the two cities would become each other's suburbs. It is of course not likely that this generation or the next will be called upon to adjust the consequent difficulties.

Another major fault of interest to alumni of the University of California is known as the Haywards fault. It marks the base of the Berkeley Hills, and it was by vertical movement along this fracture that the hills east of the Bay were given their height. The block on which Berkeley, Oakland, and other east bay towns are located was dropped down so that the waters of the Pacific could flow in and cover part of it, producing San Francisco Bay. A heavy earthquake occurred on this fault in 1868. Slight shocks, believed to originate on this fault, are felt nowadays from time to time. The writer's field studies convince him that it is an active fault. Evidence indicates that the latest movement has been an intermittent shift totalling about 1,400 feet by which the block on which Berkeley lies has moved horizontally northward by that amount with reference to the Berkeley Hills block.

In Southern California the great ranges like the San

Gabriel, San Bernardino, San Jacinto, and Santa Monica are likewise bounded on one or both sides by faults, and the mountainous character of the country is largely due to the jostling of these blocks, some rising and others sinking. The San Gabriel Mountains represent an uplifted block, now being sculptured by wind and weather and running water, while the Los Angeles plain is largely the result of subsidence and the consequent spreading over it of the erosional detritus brought down from the mountains.

Another great fault lies along the east base of the Sierra Nevada. The latter range has been uplifted along this fracture, and has been given a slope toward the west, and a very steep eastern face—the fault scarp. This fault likewise is active; in 1872 a heavy earthquake occurred in Owens Valley and a fresh scarp six feet high came into being. The summit of the range in the Whitney region presumably gained a part of six feet in altitude as a result of that slip and earthquake. The range is still growing, apparently.

That the movements of the various fault blocks have actually led to changes in geographic position, that is, in latitude and longitude, of certain points, has been amply demonstrated in the last few decades. Many peaks in the Coast Ranges, like Mt. Tamalpais and Mt. Diablo, and others in the Sierra Nevada, have had their positions determined accurately with reference to each other and to certain points whose latitude and longitude was gained by astronomical means. The angles of the triangles of which these peaks form the points have been remeasured two or more times since the first measurements of some fifty years ago. Practically all the points are found to have changed position to some extent, the shifts ranging from small distances up to twelve or fifteen feet. Even Mt. Diablo, which is the point of reference for the whole land survey net of central California and Nevada, appears to have changed its position somewhat with reference to neighboring peaks of the Coast Ranges and the Sierra Nevada.

Resurveys of peaks in southern California are reported to show similar changes in position.

To the geologist these observations appear to indicate that the earth's crust is in this west coast region in an unusually unstable condition, and that mountain-making is probably progressing as actively today as it has at any other time in earlier periods of the earth's history. He recognizes no evidence for supposing that the justling of the fault blocks will cease within any reasonable time in the future, and he is forced to believe that earthquakes will probably continue during coming centuries with about the same frequency and in general with about the same intensity as those which man has experienced thus far during his relatively short stay in the western region.

The problem in California then becomes one of *guarding against* earthquakes. And the results of studies made by seismologists and engineers indicate that with proper precautions the loss of property and of life can be kept down to trivial proportions. A full discussion of this topic is beyond the scope of this article, but a few general statements may be of interest.

In locating buildings it is obviously undesirable to place them near or on fault lines.

Areas of thick alluvium are in general less safe than areas of thin soil or bedrock. Alluvium lies in basins in the bedrock much as water lies in a metal basin; if either the rock or the metal container is shifted slightly back and forth large waves are set up in the alluvium or the water. These waves may be many times as large as those in the bedrock, and hence capable of much greater destruction. Artificially filled ground is of course still less desirable as a foundation for buildings, for it lacks consolidation and develops even larger secondary waves than ordinary alluvium. In any city in which an earthquake has wrought destruction the areas showing strikingly different effects on similar structures are usually closely coincident with the areas of bedrock, alluvium and artificially filled ground.

In designing buildings certain general rules are pertinent. The heavier a building the stronger it must be to withstand earthquake stresses. Light strong construction is hence ideal. The taller a building, the stronger it naturally must be.

For residences one-story frame structures, very well braced, with good foundations, are safer than higher buildings. Since a building should sway as a unit during an earthquake without coming apart or going to pieces, residences built of brick, cut stone, hollow tile, or concrete blocks in the usual way cannot be expected to hold together nearly as well as frame buildings, simply because these materials are difficult to bond together strongly.

In office buildings and business structures steel frame construction has withstood the most severe earthquakes. Steel skeletons are tremendously strong for their weight and for the weight of the entire building which is attached to them. They sway as units without pulling apart at critical places. Re-inforced concrete, while apparently not as earthquake proof as steel construction, is very well suited if the design, materials, and workmanship are of the proper character. Brick or terra-cotta facing of various kinds may well be used on steel or concrete structures if it is firmly attached to the frame. Large cornices, parapets, and other poorly supported parts of buildings should be reduced in size to a minimum, or better still, eliminated.

Much of the destruction at Santa Barbara, and also in San Francisco, resulted from building brick veneer fronts and walls on wood frame buildings. These walls are usually not firmly tied to the frame; it is difficult to do so. During a shock the frame building begins to sway and the brick walls, not being adapted to such antics, are pushed over by the frame and fall as a heap of bricks into the street.

In business buildings it is necessary, as it is in residences, to so build the structure that its different parts will sway together, without parting company, and in such a way that full support will not be taken away from those structural members in the building which carry the major loads.

In all our earthquakes in California well constructed buildings have stood. This teaches a practical, not a theoretical lesson. It simply means that if we build well we have little to fear from earthquakes. If we build poorly we will have repetitions of what happened at San Francisco and Santa Barbara. The question is often raised whether the added cost would not be prohibitive. The best engineering advice is that the extra cost is relatively small when the cost of the whole structure is considered.

Loss of life in earthquakes is of course related in some degree to property destruction. If buildings do not suffer the loss of life is not likely to be large. This is of course a most direct reason for good building. It has been pointed out by some that the loss of life in California shocks has been very small, relatively. But this is primarily due to the fact that our two strongest earthquakes of recent years occurred at night, with few people on the street. We should be prepared for possible daytime shocks as well.

Cities and towns should of course take steps to meet the day when a heavy shock may occur. Building ordinances should be so framed as to prevent the construction of buildings poorly suited to withstand earthquake stresses. Some California cities have taken up this problem in admirable fashion; certain others have in recent years moved in the wrong direction. If automatic trigger switches could be installed on gas and electric mains, so arranged as to cut off the flow instantly on the beginning of a strong earthquake, the danger from fire could be greatly reduced.

There is no need to be greatly alarmed or frightened about California earthquakes. They have their good qualities. It does not seem to be their habit to be accompanied by tidal waves, which are often so destructive in other countries. Statistically the danger of death from earthquakes in California is much less than from automobiles or any one of a number of common diseases. It has been calculated that if one feared an earthquake tomorrow he would run greater risk in his traveling out of the state to escape it than he would if he remained at home for the day. And experience has shown that unless we suffer much more severe shocks than have occurred within historic time, we can build against them at no greatly added cost.

It behooves us not to be alarmed, but prepared.