

ENGINEERING IMPLICATIONS OF SEISMIC GEOLOGY¹

by

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Earthquakes are generally but not exclusively concentrated in regions of youthful mountains. Such areas include very large segments of the globe, however, and history has demonstrated that there are few areas -- if any -- where the "earthquake problem" can be completely neglected. Nevertheless, by far the greatest amount of seismic activity is concentrated in the circum-Pacific and Alpine-Himalayan zones, and it is in these areas, such as the western United States and Canada, that the geologist and engineer are faced with the most challenging and continuing problems. The challenge is further complicated by the fact that engineers are constantly being asked to design larger and more imaginative structures, and alternative construction sites are continually becoming less and less available.

Earthquake epicenter maps for a given area representing a specific historical period are usually obtainable from government agencies, but the engineer must use extreme caution in drawing conclusions from such maps. On a regional basis (e.g., entire provinces and states) the presence of earthquakes in the past may indeed suggest a continuing similar activity in the future, and thus a regional "level of activity" may be established provided the recorded earthquake history is of reasonable length. But on a more local scale, of more interest to the engineer who has a specific project in mind, this relationship may completely break down, and the very areas of low activity in the recent past may be the most suspect for the immediate future. A recently completed seismicity map of southern California based on 30 years of recording may well give a somewhat reversed picture of seismicity during the next 30 years, inasmuch as segments of some of our most active faults are apparently temporarily "locked." Thus, in general, information of significance to the engineer, aside from that establishing a regional level of seismic activity, will come much more from the detailed geologic study of a particular site than from a study of the local earthquake history.

Earthquakes have long been thought to be caused by sudden shearing of rocks (i.e., faulting) following a period of elastic strain accumulation. This idea -- expressed in the classical "elastic rebound theory" -- is probably still accepted by most geologists and seismologists, although some earthquakes clearly do not fit this simple pattern. Furthermore, at the depths in the earth's crust of many kilometers where most earthquakes originate, faulting is no longer thought to be compatible

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with the theory of brittle fracture that was once assumed, but instead may involve something akin to creep instability or propagation of flaws. The close association between great earthquakes and surficial faulting, nevertheless, remains as one of the strongest arguments in favor of the fault origin of earthquakes, regardless of the exact mechanical nature of the faulting process. The great majority of earthquakes of Magnitude greater than 7 that have occurred on land and that have been carefully investigated in the field have been clearly associated with fault displacements.

The maximum recorded vertical offset on a fault during a single earthquake is about 11 meters (Assam 1897), and the maximum horizontal offset about 8 meters (Mongolia 1957). Breaks of several hundred kilometers length are not unusual during great earthquakes, and the fracturing may either start at one end and propagate to the other, or it may propagate in both directions from an initial rupture midway along the fault. In either case, the instrumental epicenter indicates only the point of initial rupture and is often many hundreds of kilometers away from the areas of greatest fault displacement and greatest intensity of shaking. In those cases where the displacement is primarily horizontal, the faulting has generally been confined to one principal linear break (e.g., San Francisco 1906, North Anatolia 1939), whereas significant vertical components have more often been associated with sinuous, branching, or disconnected fractures, together with regional warping (e.g., Assam 1897, Alaska 1964). Faulting is basically a shear failure under compressive stress (vertical or horizontal), so that extensive "gaping" of fractures is not to be expected except locally in soils and similar near-surface materials.

Two aspects of faulting are of particular interest to the engineer: (1) How does one go about determining the existence of a fault and locating its trace, and (2) once located, what determines its engineering significance, if any? Various criteria for the recognition of faults in the field are given in every structural geology textbook, but they all basically depend on the recognition of evidence that finite displacements have taken place on a plane of shearing. Such evidence includes fault gouge and breccia, juxtaposition of differing rock types, truncation of structures, slickensides, and anomalous physiographic features. In general, the gathering of these types of evidence and their interpretation demand detailed geologic mapping of the entire area in question, inasmuch as faults cannot be divorced from other aspects of the local and regional geology. For example, determination of a fault's history of displacement which may in turn have a decided bearing on its degree of current activity -- frequently depends more on regional stratigraphic and paleontological studies than on observations of the fault itself. Physiographic evidence of faulting is particularly important in engineering studies because the ground surface is a young and ephemeral feature, and any disruption of the ground surface implies relatively recent faulting that usually suggests continued activity into the future. Physiographic features commonly

associated with active faults include fault scarps, sag ponds, springs, elongated closed depressions, side-hill ridges, and ground-water barriers. Aerial photographs are a virtual necessity for recognition of these features and should be one of the first reconnaissance tools employed. Exploratory trenches should also be excavated across suspicious features before the commitment to the site or to a particular design becomes too firm. In the case of a dam at a questionable site, it is particularly important that there be an opportunity to reappraise the entire program after stripping of the overburden has taken place, inasmuch as it may be only at this time that the details of the geology become relatively well known. Except under very unusual circumstances, faults cannot be detected and delineated by the detailed seismographic locations of earthquakes, and a seismograph network at a specific site can do little more than contribute to the overall knowledge of the level of regional seismicity.

Once the existence of a fault is demonstrated, the determination of its degree of current activity is a difficult, frustrating, and sometimes impossible problem to solve -- yet obviously one of profound engineering importance. In general, it is far easier to recognize a fault than to decide how "important" it is! There is good reason to believe that faults that have undergone displacements most continuously and most recently in the geologic past are the most likely candidates for future displacements, and the geologist can often rank faults in this manner -- based on such lines of evidence as detailed physiographic observations, Carbon 14 dating, soils studies, and the historic record. But this is still a far cry from the assignment of an actual numerical probability of displacement during a specified time interval, and the problem becomes particularly acute with the less active and "dead" faults that are more apt to be the proposed sites of engineering structures. Renewed displacements on seemingly "dead" faults are by no means unknown in the historic record. At the moment, the geologist can only state with assurance that the probability of a fault displacement at one site is much greater or less than at another, but the growing optimism among earth scientists that earthquake prediction may be within the realm of possibility suggests that the assignment of quantitative probabilities of fracturing on a given fault is not a completely unrealistic goal for the future.

Even if the geologist cannot accurately assess the probability of displacement on a given fault during the life of an engineering structure, he may be able to predict confidently what the sense of displacement would be if the break were to indeed take place. This may be of particular value in the planning of facilities such as dams and aqueducts, where the orientation or layout of the structure may be designed to minimize the damage resulting from the specified displacement.

Documentation in recent years of several localities where slow, continuous slippage (i.e., "creep") is taking place along faults demonstrates another possible hazard of active faults aside from earthquakes

themselves. Geologists and seismologists are now suspicious that such slippage may be a much more prevalent phenomenon along active faults than was suspected only a few years ago. In general, however, careful geodetic surveying programs across a suspected feature should be able to demonstrate significant movements of this type, and surveys with this objective in mind should certainly now be a routine procedure at any construction site where active faults are suspected.

Although faulting may be the most obvious geologic manifestation of major earthquakes, it is by no means the most important factor from an engineering viewpoint. Recent major earthquakes in Chile, Japan, and Alaska have dramatically illustrated the widespread and devastating effects of earthquake-induced landslides and soils failures, together with the markedly differing intensities of shaking depending on local geologic conditions. In most construction sites in seismic areas, and particularly in those of high relief, earthquake-triggered landslides and related soils failures pose a much more severe engineering problem than does the possibility of actual faulting through the site. This obviously calls for the most careful studies by experts in both geology and soil mechanics, and no simple answers can be prescribed. From the geological point of view, the importance of understanding the regional geology as well as that at the particular site should again be emphasized; landslide hazard often depends on such seemingly abstruse factors as the nature of joint patterns, stratigraphic details, ground-water regimen, clay mineralogy, and recent erosional history, as well as on the very local morphology. The differing intensities and periods of shaking in different geologic environments (e.g., bedrock vs. thick alluvium) represent an important problem on which much further research is badly needed, inasmuch as most information available to date is qualitative rather than quantitative. It is clear from the historic record, however, -- demonstrated most recently in the 1964 Alaskan earthquake -- that within a very wide region, proximity to the epicenter or the fault may be secondary to local geologic conditions in terms of seismic hazard from shaking.

Seismic zoning maps for engineering purposes have usually been constructed on the basis of the earthquake history of a region, sometimes in combination with the locations of so-called "active" faults and related seismo-tectonic features. Indeed, these are normally the only items of pertinent information available -- however inadequate. It should be emphasized, however, that these data may be even far more inadequate than most people realize. The difficulties and dangers in interpreting a relatively short recorded earthquake history, as well as the problems in attempting to differentiate between active and inactive faults, have already been pointed out, together with the very widespread distribution of earthquake-induced effects during a great shock. In addition, major after-shocks of a great earthquake are distributed over a far wider area than has generally been appreciated, and they constitute a hazard that may seemingly be quite unrelated to the local fault pattern. Poten-

tially damaging aftershocks of the 1960 Chilean earthquake, for example, blanketed an area almost the size of California. It is significant that those countries with the longest and most complete recorded earthquake histories are generally those in which the mapped zones of potential high seismic hazard are the broadest, and this lesson should be kept in mind by those persons attempting to construct new zoning maps or by engineers who are facing the same problems with regard to specific sites.