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Chapter 12

Faulting and Seismic Activity

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INTRODUCTION AND HISTORY

This chapter traces some of the ideas and concepts leading to the current understanding of the process of faulting and earthquake generation, gives examples of engineering geology investigations contributing to that understanding, describes some engineering projects that have been strongly influenced by the process, and suggests needed research. Each of these topics is discussed in sequence.

The understanding of faulting and earthquakes and of the significance of these to engineering has developed over several centuries. John Michell in 1761 was probably the first to publish a cross section of a clearly recognizable fault (Adams, 1938, Fig. 66). Michell did not attribute earthquakes to faulting, but proposed the important idea that seismic vibrations were the result of the propagation of elastic waves in the earth (Adams, 1938). Charles Lyell (1830) emphasized the uplift and depression of land that accompanies earthquakes. He did not attribute earthquakes to faulting, but a contemporary of his evidently did, for the following statement appeared in a review of Lyell's book (Scrop, 1830, p. 463):

> The sudden fracture of solid strata by any disruptive force must necessarily produce a violent vibratory jar to a considerable distance along the continuation of these strata. Such vibrations would be propagated in undulations, which may be expected, when influencing a mass of rocks several thousand feet at least in thickness, to produce on the surface exactly the wave-like motion, the opening and shutting of crevices, the tumbling down of cliffs and walls, and other characteristic phenomena of earthquakes.

This idea was apparently disregarded, and coseismic faulting, some of which reached the ground surface, was generally considered to be the result rather than the cause of earthquakes until the time of G. K. Gilbert. Gilbert was the first to clearly state that faulting is the cause of earthquakes. Furthermore, Gilbert used the "modern" concepts of stick-slip, elastic strain accumulation, and seismic gaps to make an earthquake forecast for the Salt Lake City, Utah, area in 1883 (Gilbert, 1884). However, these ideas and others related to the study of faults were overlooked for many decades (Wallace, 1980).

The definitive paper relating earthquakes to faulting was that of Reid (1910) who proposed that the 1906 California earthquake resulted from slow accumulation of elastic strain followed by faulting and elastic rebound. More recently, Tocher (1958) demonstrated that surface faulting usually accompanied earthquakes of magnitude 6.5 or greater in northern California and Nevada; he was the first to relate earthquake magnitude to surface rupture length and to the product of length and displacement. The relation of rupture length to earthquake magnitude was

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applied by Benioff (1965) and by Albee and Smith (1967) to the problem of estimating earthquake size in connection with the Malibu reactor site, described in this chapter. Systematic compilation of data relating surface-fault dimensions to earthquake magnitude have been made by various investigators, including Bonilla (1967, 1970) for events in North America, and for events throughout the world by Bonilla and Buchanan (1970), Slemmons (1977, 1982), and Bonilla and others (1984).

Using earlier theoretical work, Aki (1966) introduced a new measure of earthquake size, the seismic moment, which is related to the area of the fault surface, the average fault displacement, and the shear modulus of the rock. By this method, the average coseismic subsurface displacement on a fault can be estimated from seismograms. Brune (1968) showed that the rate at which seismic moment is released can be translated into slip rate on the fault. The converse, translation of fault slip rate into rate of production of earthquakes in terms of seismic moment, has led to the use of geologic data on slip rate to estimate earthquake rate in a given time interval (Anderson, 1979; Molnar, 1979; Wesnousky and others, 1984). Seismic moment can be converted to the more commonly used earthquake magnitude over a wide range of magnitudes (Hanks and Kanamori, 1979).

Geologic studies of the recent history of faults, especially using exploratory trenches, have led to the identification of prehistoric episodes of faulting and, by inference, of prehistoric seismic events. The use of exploratory trenches for such studies became common in the 1970s (e.g., Malde, 1971; Clark and others, 1972; Bonilla, 1973; Sieh, 1978) and allowed inferences to be made regarding the seismic history of particular faults or regions extending back thousands of years (Sieh, 1981).

The “characteristic earthquake” or “maximum earthquake” model of fault behavior, if it is proved to be substantially correct, will have an important effect on estimates of expected earthquakes and fault dimensions. This model suggests that the earthquakes and the dimensions of faulting on a given fault or fault segment are of nearly equal size in each succeeding event. This idea was implicit in papers by Allen (1968), Wallace (1970), and Matsuda (1975), and was explicitly developed in papers by Swan and others (1980), Wesnousky and others (1983), and especially Schwartz and Coppersmith (1984).

The significance of faulting to engineering works was incisively discussed by Louderback (1937, 1942, 1950), and data on faulting were compiled for engineering purposes by Bonilla and colleagues and by Slemmons in papers cited above. Other papers have discussed the importance of faulting, including design considerations, for particular types of structures. Among such papers are Sherard and others (1974) on dams; and Newmark and Hall (1974, 1975), Hall and Newmark (1977), Taylor and Cluff (1977), and McCaffrey and O’Rourke (1983) on pipelines.

CONTRIBUTIONS OF INVESTIGATIONS FOR ENGINEERING WORKS TO KNOWLEDGE OF FAULTING AND SEISMICITY

Geological and geotechnical investigations for various kinds of engineering works have contributed directly to the sum of knowledge about faulting and seismic activity and, perhaps more importantly, have stimulated topical research. Site- specific investigations have provided concentrated information on local and regional geology and faults. Topical research has shed light on the process of faulting and earthquake generation, its effects on engineering works, and on ways to investigate the process. Research initiated in response to problems on one project is commonly found to be of general application. A few examples follow.

Sheffield and Lower San Fernando dam

Many earth dams have been damaged by earthquakes, but only two are discussed here. Study of the failures was important in advancing the art of analyzing the stability of slopes during earthquakes. The Sheffield Dam near Santa Barbara, California, constructed in 1917, was 8 in high and contained a pool 5 m deep at the time of the 1925 Santa Barbara earthquake. The earthquake produced a maximum acceleration estimated to be 0.15 g at the dam, under which the embankment failed completely (Seed and others, 1969, 1978); fortunately little damage and no loss of life resulted. Failure was by liquefaction, apparently in the silty sand and sandy silt just below the dam embankment.

The Lower San Fernando Dam (sometimes called the Lower Van Norman Dam) northwest of Los Angeles, California, constructed by hydraulic fill methods in 1916, was enlarged to a final height of 43 m in 1930. The older part of the dam has a clay core and outer zones of silty sand. The water depth was 27 m at the time of the February 9, 1971, earthquake, which produced a maximum acceleration of about 0.6 g at the dam (Scott, 1973; Seed, 1979). Liquefaction in the upstream sand zone led to a major slide that involved the clay core and took out the crest along nearly half the length of the dam, leaving a rim of cracked fill only 1.4 m above water level (Fig. 1). Because of this dangerous condition, 80,000 people living

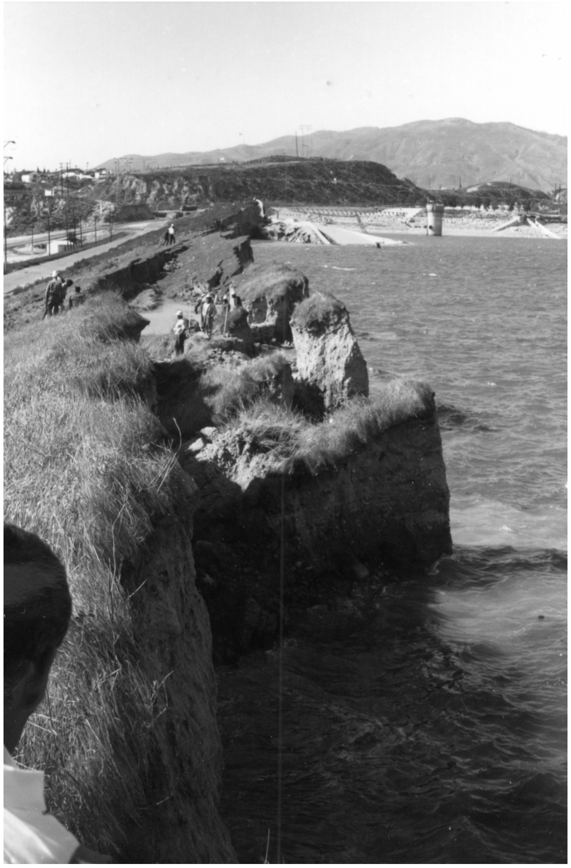

Figure 1. Remains of crest of Lower San Fernando Dam, damaged by a landslide following the magnitude 6.5 earthquake of February 9, 1971. Men on left are looking down at reservoir water, which is only 1.4 m below them. One outlet tower is visible in the right background; the other tower was knocked down by the landslide and was submerged in the reservoir. Photograph by T. L. Youd, U.S. Geological Survey, February 9, 1971.

downstream were evacuated (Ross, 1975; Seed, 1979). Analyses of these and other case histories by Seed and his colleagues showed that the conventional method of pseudostatic analysis of slopes under seismic loading is inadequate when applied to saturated cohesionless soils, and dynamic analyses are needed (Seed and others, 1975; Seed, 1979). As a result of the near catastrophe in San Fernando, the State of California instituted a reevaluation of existing embankment dams throughout the State (Babbitt and others, 1983).

Bodega Head and Malibu nuclear reactor sites

The Bodega Head and Malibu sites were the first nuclear sites in the United States for which active faults were an important consideration. Investigation of these sites in the 1960s stimulated research on fault behavior and led to concepts regarding site evaluation that have been applied to the siting of reactors, dams, pipelines, waste-disposal facilities, and other engineering works.

The Bodega Head reactor site, 82 km north-northwest of San Francisco, California, is about 0.3 km from the poorly defined western edge of the San Andreas fault zone and about 2.1 km west of the 1906 fault trace (Fig. 2). Investigation and site preparation began in 1958 and terminated in 1964 (Novick, 1969). Because of the proximity of the site to the San Andreas fault, site excavations were minutely examined as they progressed. During excavation of the shaft for the reactor, a fault (Fig. 3) was found in the unconsolidated sediments overlying the quartz diorite bedrock. Mapping of the shaft fault showed that (1) where exposed in the sediments, it died out horizontally in at least one direction; (2) in some places it died out downward in the sediments, but in other places it joined a fault zone in the bedrock; (3) it was not visible in certain sedimentary layers but was clearly visible above and below those layers; and (4) it could not be traced to the ground surface (Schlocker and Bonilla, 1963, 1964). The discovery of the fault and its characteristics raised several debated questions. Was the ‘fault’ merely the edge of a landslide in the unconsolidated sediments whose flank happened to coincide with an underlying fault in bedrock? Moreover, inasmuch as the fault was not visible in certain sedimentary layers, and strike-slip faults such as the shaft fault commonly have discontinuous traces (Schlocker and Bonilla, 1963), was the last displacement on the fault older than the apparently overlying beds or had it just become unrecognizable or died out upward? Although located outside the San Andreas fault zone, was the shaft fault likely to have displacement when the next movement occurred on the San Andreas fault? To answer some of these questions, a thorough review was made of the surface ruptures accompanying the 1906 earthquake (Schlocker and Bonilla, 1964).

The study showed that even though the field investigation of the 1906 faulting was mostly limited to the main trace, several ruptures were reported at a distance from the main trace, including some ruptures several kilometers away, well outside the San Andreas fault zone itself. This finding had an important bearing on the evaluation of the fault at the Bodega Head site and raised questions about the existing Atomic Energy Commission regulations, which stated that a nuclear reactor should not be placed “closer than one-fourth mile from the surface location of a known active earthquake fault” (U.S. Atomic Energy Commission, 1962, p. 3510). In performing research sponsored by the Atomic Energy Commission on this problem, Bonilla compiled data on subsidiary faulting and, at the same time, on the relation of earthquake magnitude to surface rupture length and displacement for historic events in the U.S. (Bonilla, 1967, 1970).

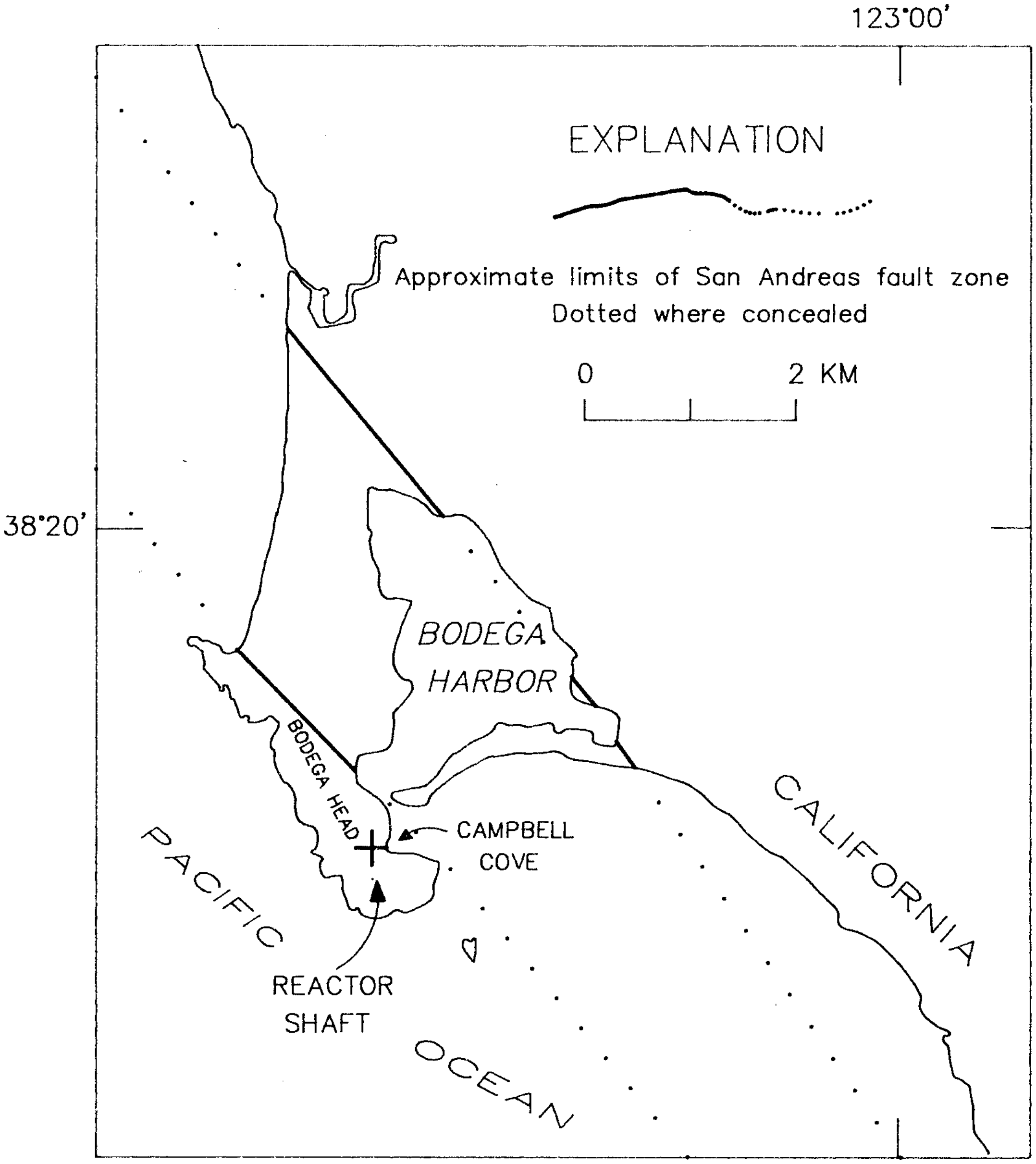

Figure 2. Map showing relation of Bodega Head nuclear reactor site to San Andreas fault zone. The 1906 surface rupture on the San Andreas fault was near the northeastern edge of the fault zone. Modified from Schlocker and Bonilla, 1963, Plate 1.

This research was later extended to include historic surface ruptures in other parts of the world (Bonilla and Buchanan, 1970; Slemmons, 1977, 1982; Bonilla and others, 1984). The phenomenon of fault traces being unrecognizable or obscure in certain layers led, much later, to research that is currently in progress on the conditions under which this might occur and how it may affect the interpretation of exploratory trenches across faults (Bonilla, 1985).

Figure 3. Shaft fault as seen in vertical section during excavation of reactor shaft at Bodega Head site. In Quaternary beds, the maximum observed vertical separation on the fault was 0.36 m; a strike-slip component was recognizable but was of unknown amount. In the granitic bedrock the observed strike-slip component was 7.3 m and the fault was 0.6 to 3.0 m wide. Photograph by Julius Schlocker, U.S. Geological Survey, 1963.

The Malibu nuclear reactor site, on the coast 45 km west of Los Angeles, California, lies within the Malibu coast zone of deformation and just south of the Malibu coast thrust fault, a major east-west fault with principal movement between late Miocene and late Pleistocene. Investigations related to the project showed that a fault of unknown age traversed the proposed location of the reactor containment vessel and that several faults having displacement in the late Pleistocene existed in the Malibu coast zone outside the plant site (Yerkes and Wentworth, 1965). In addition to these local conditions, the regional setting was an important factor in evaluation of this site. The site lies in an east-west belt of moderate seismicity that contains the Malibu coast zone. This zone forms the northern border of a structural block whose eastern border is inferred to be 30 km to the east, along the right-lateral, northwest-trending Newport-Inglewood zone of faults and folds, which has been active in the Holocene (Fig. 4). The inference was made that the structural block is currently moving relatively northward, with right-slip on its eastern border and thrusting on its northern border. This combination of local and regional evidence led to the conclusion that the east-west structural zone containing the nuclear reactor site is tectonically active (Yerkes and Wentworth, 1965; Marblehead Land Company, 1966). The value of such regional analysis is recognized in the U.S. nuclear plant siting criteria, which, in defining a capable fault, includes those faults that exhibit ". . . a structural relationship to a capable fault ... such that movement on one could be reasonably expected to be accompanied by movement on the other" (U.S. Nuclear Regulatory Commission, 1977, p. 413).

The few existing data relating fault length to earthquake magnitude were used to some extent in estimating the size of potential earthquakes near the Malibu site (Benioff, 1965; Albee and Smith, 1967). The need for more complete data led to compilations of fault length versus magnitude during the study of historic faulting by Bonilla (1967) that was started as a result of the problems related to the Bodega Head investigation.

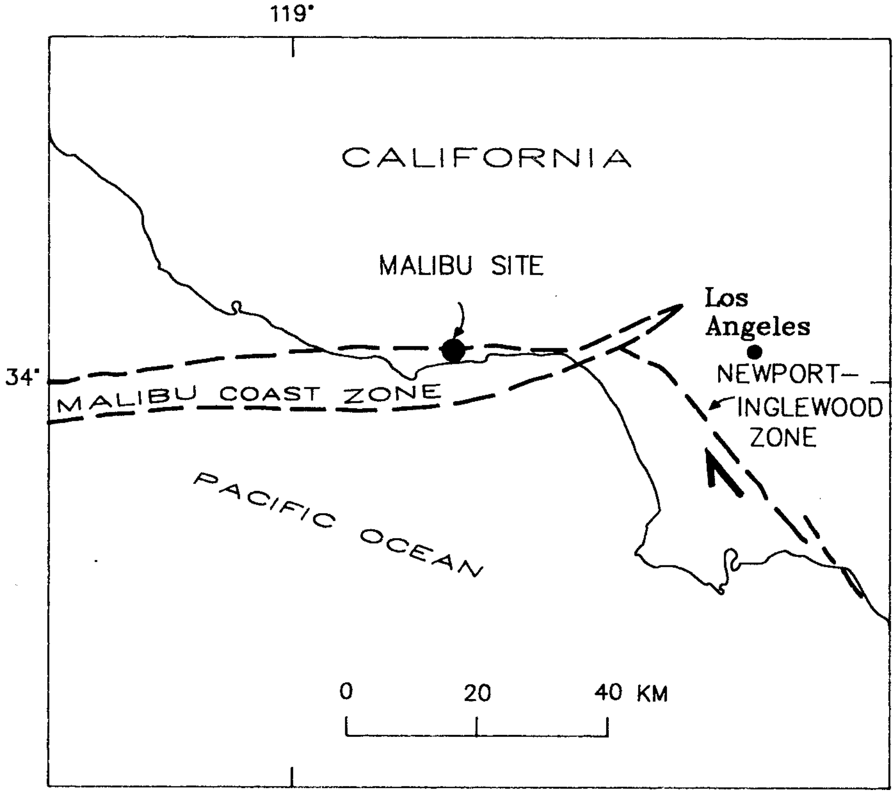

Figure 4. Sketch map showing relation of Malibu Coast zone of deformation to the Newport-Inglewood zone of faults and folds, and location of Malibu nuclear reactor site. Modified from Yerkes and Wentworth (1965, Fig. 44).

Investigations directly or indirectly related to the Bodega Head and Malibu nuclear reactor sites had effects on the U.S. reactor site criteria in addition to those already mentioned. The term “known active earthquake fault” in the criteria during the early 1960s was ambiguous and taken by some to mean a fault with historic surface rupture and by others a fault with rupture in the past 10,000 years. At Malibu, faults whose most recent displacement was between 10,000 and about 180,000 years ago were nevertheless considered capable of surface rupture for purposes of reactor design (Atomic Safety and Licensing Board, 1966; U.S. Atomic Energy Commission, 1967). This finding strongly influenced the wording in the new site criteria, which were in preparation, and led to the inclusion of “Movement at or near the ground surface at least once within the past 35,000 years or of a recurring nature within the past 500,000 years” as part of the definition of capable fault (U.S. Nuclear Regulatory Commission, 1977, p. 413). The necessity to consider evidence at a distance along the strikes of the San Andreas and Malibu coast zones to evaluate the risk of faulting at the Bodega Head and Malibu sites is also reflected in the wording of the criteria. Furthermore, the requirement to determine the capability of faults within 8 km of a reactor site and the inclusion of monoclinal flexure in the criteria are a direct outcome of information uncovered in the review of historic surface faulting in the U.S. that resulted from the Bodega Head investigations. Much of the wording and many of the concepts in the U.S. Nuclear Regulatory Commission (1977) criteria have since appeared, in modified form, in guidelines of organizations that are concerned with dams, with disposal of hazardous waste, or with liquefied natural gas facilities.

Trans-Alaska Pipeline System

The Trans-Alaska oil pipeline, which cost more than $8 billion (Godfrey, 1978), was the most costly engineering project ever undertaken by private industry. Solution of the associated environmental problems contributed to knowledge in many fields, including permafrost, seismic hazard evaluation, and the engineering of pipelines that must cross permafrost, areas of high seismicity, and active faults. The 1.2-m-diameter steel pipeline, planned and built in the period 1968 through 1977 (Roscow, 1977), crosses Alaska from north to south, a distance of 1,287 km (Fig. 5).

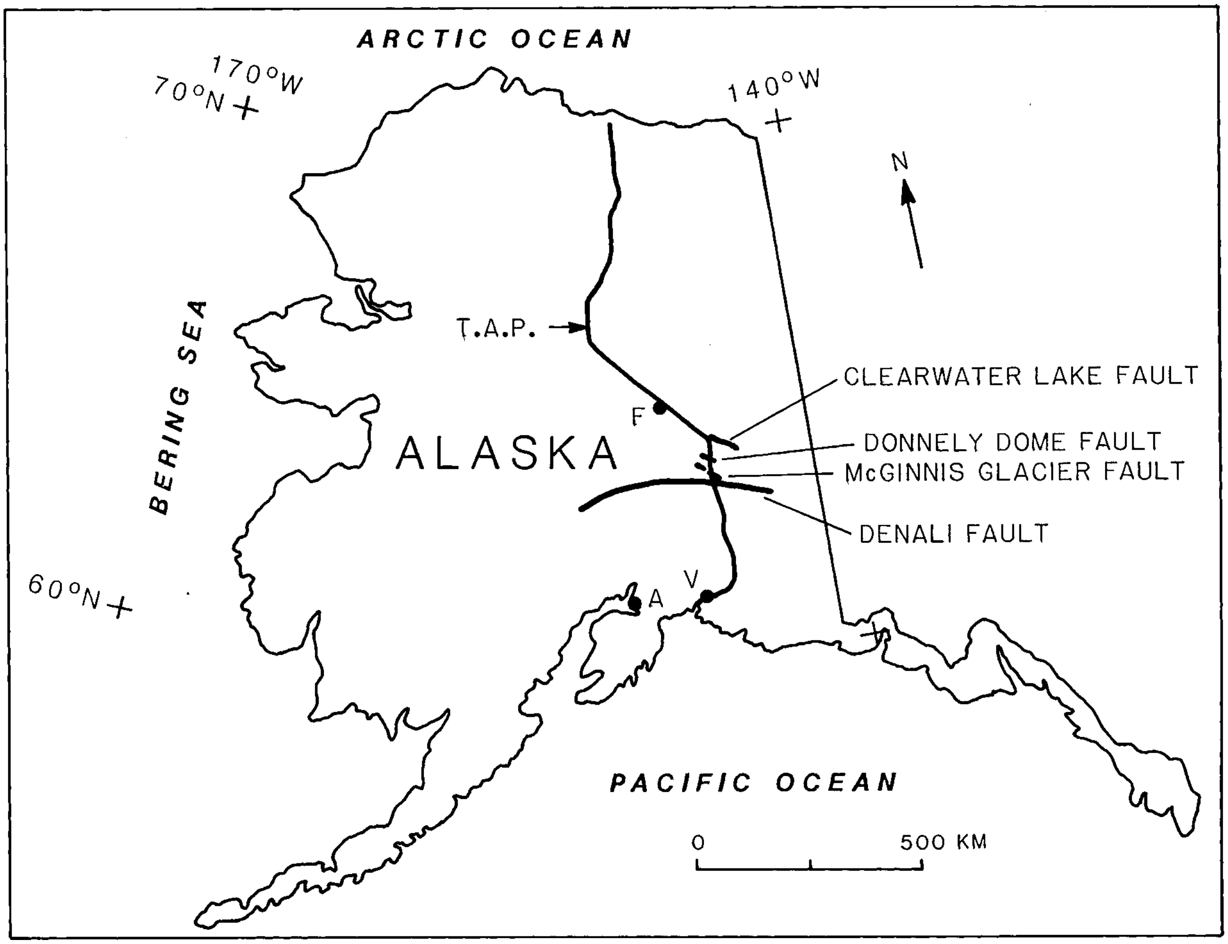

Figure 5. Outline map of Alaska showing Trans-Alaska pipeline (T.A.P.) and the four faults identified as active and of concern to the pipeline. F, Fairbanks; A, Anchorage; V, Valdez. Faults are from Brogan and others (1975, Fig. 2); location of pipeline from Brew (1974, Fig. 1).

In the early stages of planning, not much was known about the seismicity or the activity of faults in the vast area to be crossed by the pipeline. On the basis of available data, five seismic zones having earthquake potential ranging from magnitude 5.5 to 8.5 were outlined, the required fault investigations were described, and the stipulation was made that no storage tank or pump station was to be located in an active fault zone (U.S. Federal Task Force on Alaskan Oil Development, 1972).

Investigations to identify active faults covered about one-third of the state of Alaska. These investigations included extensive use of helicopters and fixed-wing aircraft, and study of aerial photographs, satellite imagery, radar imagery, and low-sun angle photography. About 8,000 lineaments were identified; of these, four that crossed the pipeline were faults considered to have the potential for surface rupture (Cluff and others, 1974; Brogan and others, 1975). The fault investigations just described were done for the Alyeska Pipeline Service Company, but other investigations on a smaller scale were also done by the U.S. Geological Survey and by environmental groups. These studies greatly enhanced understanding of the location, dimensions, and Quaternary activity of faults in a very large part of the state of Alaska.

The potential effects of the design earthquakes stipulated in the environmental impact report (U.S. Federal Task Force on Alaskan Oil Development, 1972) had to be translated into the design of the pipeline. The existing data on earthquake ground motion were critically reviewed and presented in the form of plots of peak acceleration, peak velocity, peak displacement, and duration as a function of earthquake magnitude and distance to the slipped fault (Page and others, 1972). Duration of shaking was expressed in terms of a new parameter—the interval between the first and last acceleration peak equal to or greater than 0.05 g—that could be readily scaled from existing accelerograms and would approximate the time over which the ground accelerations exceed the given level. This parameter was subsequently termed bracketed duration (Bolt, 1974). From these data, estimates of near-fault peak ground motions and durations were drawn for magnitudes 5.5 through 8.5 (Page and others, 1972). These ground-motion estimates, together with estimates of surface fault displacements, were then used by engineers as a basis for design of the pipeline to resist both shaking and faulting (Newmark and Hall, 1974, 1975). The estimates of surface fault-displacement (Cluff and others, 1974) were based partly on data (Bonilla and Buchanan, 1970) that were compiled because of the problems associated with the Bodega Head and Malibu nuclear reactor sites.

The Trans-Alaska pipeline project contributed to geoscientific knowledge in several ways, only a few of which are described above. Investigation of relevant geological problems resulted in (1) an improved understanding of seismic zonation and Quaternary faulting in Alaska, (2) translation of expected earthquake magnitudes into data useful in design, and (3) design of pipelines to resist both earthquake shaking and surface faulting. The near-fault ground motion estimates in the report by Page and others (1972) incorporated an extensive new suite of strong-motion recordings from the 1971 San Fernando, California, earthquake (magnitude 6.6); the estimates were highly controversial because they indicated more intense shaking would occur close to the fault than had been typically assumed by seismic engineers for the design of important structures (see for example, Housner, 1970, p. 79-80). These ground-motion estimates affected not only the design of the Trans-Alaska pipeline system but also the design of other critical facilities such as nuclear reactors (see Diablo Canyon Nuclear Power Station, described below) and dams (e.g., the Los Angeles Dam, Wesson and others, 1974). These studies for critical structures also raised concern about the earthquake resistance of more ordinary structures (Page and others, 1975). Some effects of the potential earthquakes and the presence of active faults on the design and construction of the pipeline are discussed in a following section.

Little Cojo Bay Liquefied Natural Gas Terminal

In connection with the planned Little Cojo Bay Liquefied Natural Gas Terminal in Santa Barbara County, California, extensive local and regional geological and geophysical studies were made, and topical research was initiated. During the investigation, faults considered capable of surface rupture were identified at the site (Slosson and Associates, 1981). The necessity to consider faulting led to additional research on three different topics: (1) centrifuge and numerical modeling of the propagation of faults through soils to better interpret the geologic history of displacements of faults and to assist in design of structures in fault zones (Roth and others, 1981a, 1982), (2) laboratory testing and analysis of the process of fault rupture through alluvium to better predict the width and inclination of rupture zones associated with dip-slip faults (Cole and Lade, 1984; Lade and others, 1984), and (3) numerical and laboratory modeling of bedding-plane faulting accompanying flexural slip (Roth and others, 1981b). The results will no doubt be applied to other projects, if due consideration is given to the differences between laboratory and field conditions.

Nuclear waste repository sites

Investigations for repository sites for nuclear wastes include special aspects that set them apart from typical engineering works. Most projects have a design lifetime and therefore a period of concern for safety of 50 to 100 years, whereas for geologic disposal of nuclear wastes the period of concern is 10,000 years or more (U.S. Department of Energy, 1985). To anticipate the effects of geologic processes so far into the future requires a profound knowledge of the rates and changes in rates of those processes in the vicinity of the site. Consequently these studies produce a wealth of geoscience information on various topics, including current and past seismicity, tectonics, and stress fields. For example, the reader is referred to the studies for the potential high-level nuclear waste repository site at Yucca Mountain, Nevada (U.S. Geological Survey, 1984; Stock and others, 1985; Frizzell and Zoback, 1987).

IMPACT OF FAULTING AND SEISMICITY ON ENGINEERING WORKS

The impact of faulting and seismicity on engineering works is of two general kinds: direct damage, and increased costs incurred to avoid damage from future events. Among the increased costs are design changes, delays, and complete abandonment of some projects. The emphasis in this section is on projects that were strongly affected by anticipated future faulting and earthquakes. Costs are given in dollars if readily available; however, the costs are not directly comparable between projects because they are not adjusted for inflation.

Structures of many kinds have been directly damaged, to various degrees, by faulting. The damaged structures include embankment dams, tunnels, bridges, roads, railroads, nursing homes, commercial buildings, apartments, houses, canals, storm drains, water wells, and water, gas, and sewer lines. Fault damage to structures is described in many reports (Lawson and others, 1908; Louderback, 1937; Ambraseys, 1960; Duke, 1960; California Department of Water Resources, 1967; Subcommittee on Water and Sewerage Systems, 1973; Niccum and others, 1976; Hradilek, 1977; Youd and others, 1978; Sylvester, 1979; Gordon and Lewis, 1980; McCaffrey and O’Rourke, 1983; Pampeyan, 1986). Damage to the Baldwin Hills reservoir made possible by displacement on a fault is discussed in Holzer (this volume) and James and Kiersch (chapter 22, this volume). Innumerable buildings and a few dams, including the Sheffield and Lower San Fernando dams described above, have been severely damaged by earthquake vibrations. Other projects have been affected by postulated future events; some of these projects are described below.

Bodega Head nuclear reactor site

This reactor site was abandoned, after an expenditure of $4 million for planning and construction (Novick, 1969), because of the shaft fault described above and the possibility of a large earthquake on the nearby San Andreas fault during the 50-year design life of the plant. The proximity of the shaft fault to the San Andreas, its similar sense of displacement, and the uncertain age of its last displacement meant that the possibility of faulting under the reactor had to be considered. The applicant proposed a design that would accommodate 0.9 m of either horizontal or vertical shearing by faulting. The proposed design was approved in principle by the Advisory Committee on Reactor Safeguards, but the Division of Reactor Licensing of the Atomic Energy Commission and its consultants held that, although the design might protect the reactor from faulting, the piping and other connections leading out of the reactor probably could not withstand both the faulting and the shaking from the expected magnitude 8+ earthquake on the San Andreas fault. Furthermore they stated that “experimental verification and experience background on the proposed novel construction method are lacking,” and concluded that “Bodega Head is not a suitable location for the proposed nuclear power plant at the present state of our knowledge” (U.S. Atomic Energy Commission, 1964, p. 13, 14). On October 30, 1964, three days after this statement was released, the utility announced that it had abandoned plans for a nuclear power plant at the site (Novick, 1969).

Malibu nuclear reactor site

After public hearings and other reviews of the problems relating to faulting and seismicity, some of which are discussed above, the Atomic Energy Commission ordered that the proposed Malibu reactor would have to be designed to accommodate fault displacement. Both the amount of differential ground displacement and the adequacy of any proposed design criteria to accommodate the displacement were required to be determined (U.S. Atomic Energy Commission, 1967). Six years later, the applicant withdrew the construction permit application (letter from Los Angeles Department of Water and Power to U.S. Atomic Energy Commission dated May 30, 1973), and the project was abandoned. No estimate of the cost of the project to the applicant is at hand but it is surely greater than the $4 million cost of the Bodega Head project.

Diablo Canyon Nuclear Power Station

The discovery of an offshore fault while the Diablo Canyon Nuclear Power Station was under construction caused many delays and greatly increased the cost of the plant. Construction of the plant, which is on the central California coast 20 km south-southwest of San Luis Obispo, started in 1968. A report on petroleum provinces of the United States, published in 1971, contained a map showing an unnamed fault lying a short distance offshore from the plant site (Hoskins and Griffiths, 1971). A small-scale cross section in their report indicates that the contact between lower and upper Pliocene sedimentary units has been affected by faulting, but the fault was not discussed in the text.

In 1973 the U.S. Atomic Energy Commission supported offshore work by the U.S. Geological Survey to investigate faulting and other possible hazards. The investigation included subbottom acoustic reflection profiling, bathymetry, and recording of the magnetic field over a track length of 1,200 km that covered an area some 13 km wide by 124 km long (Wagner, 1974). This study confirmed the presence of the fault reported by Hoskins and Griffiths and named it the Hosgri fault after them. The investigation determined that the fault has strike-slip as well as dip-slip displacement, that it possibly cuts late Quaternary sediments in some places, and that some earthquakes have occurred along its length (Wagner, 1974).

Various other studies and analyses related to the seismic potential of offshore faults were subsequently performed by the applicant and other groups (Earth Sciences Associates, 1974). After review of these and other studies, the U.S. Geological Survey concluded in 1975 that a magnitude 7.5 earthquake could occur on the Hosgri fault about 5 km from the nuclear plant

(U.S. Nuclear Regulatory Commission, 1976, Appendix C) and that the ground-motion values derived for the Trans-Alaska pipeline system (Page and others, 1972) should be used as a starting point for the seismic design analysis (U.S. Nuclear Regulatory Commission, 1976, Appendix C, p. C-16). The suggested magnitude 7.5 earthquake and associated ground-motion parameters were much larger than those considered in the design and construction of the plant; consequently, extensive reanalyses of the plant were required, and many parts of the plant had to be modified (Lawroski, 1978; Piper, 1981). Furthermore, a license condition that was added to the operating license for the plant requires that the design earthquake and resulting ground motions be reevaluated by about 1988, using new information and interpretations (Brand, 1985). The original cost estimate for Diablo Canyon Nuclear Power Station was $350 million, but by 1979 its cost was $1.4 billion (San Jose Mercury News, 1984). An unknown, perhaps substantial, fraction of the increase in cost is attributable to the postconstruction discovery of the Hosgri fault, and more costs were subsequently incurred when flaws in the seismic design were found in 1982 (San Jose Mercury News, 1984). In considering the significance of the increase in cost given above, one should keep in mind that many nuclear plants, including some in the eastern part of the United States where earthquakes are not a major problem, have cost six to nine times more than originally projected (Dallaire, 1981; Cook, 1985).

Trans-Alaska Pipeline System

Permafrost presented the most critical geologically related problems to the pipeline (Lachenbruch, 1970; Roscow, 1977), but earthquakes and faulting were also important—economically and technically—in several ways. The pipeline system had to accommodate potential effects of the design earthquakes and surface faulting. Accelerographs were installed at 11 places along the pipeline to automatically detect, evaluate, and transmit strong-motion data to a central terminal at Valdez (Roscow, 1977; Péwé and Reger, 1983). Because of extreme temperature variations and other considerations, the elevated segments of the pipeline normally rest on shoes that allow the pipe to move sideways and upward, except at certain anchor points. This construction mode, which applies to about half of the pipeline, can accommodate some movement resulting from earthquakes and faulting as well as from thermal effects.

Fault design parameters were given by Cluff and others (1974) for four faults considered to be active (Fig. 5). The four faults and the corresponding design parameters, given in terms of fault shift (the combination of fault slip and fault distortion or drag across the fault zone) in the strike-slip and dip-slip directions, respectively, are: Denali fault, 6.1 m and 1.5 m; McGinnis Glacier fault, 2.4 m and 1.8 m; Donnelly Dome fault, 0.9 m and 3.0 m; and Clearwater Lake fault, 2.1 m and 3.0 m. Suggested special designs for fault crossings (Newmark and Hall, 1974; Hall and Newmark, 1977) included placing the pipe on beams at ground level on which it can slide and, in bedrock, placing the pipe in a shallow gravel-filled trench whose sides slope at 45° or less so that the pipe can move up and out of the trench. In the above-ground mode of installation the pipe can resist about 1.2 to 1.5 m of vertical displacement without undue strain, especially if it is free to accommodate the displacement over large distances (Hall and Newmark, 1977). Because the exact location of active fault traces within the active fault zones was not known and the pipeline crossed the zones at oblique angles, design modifications had to be considered for long segments of the pipeline.

The crossing of the Denali fault, on which the largest fault displacements were anticipated, is illustrated in Figure 6. The part of the pipeline in the fault zone rests on beams placed on a gravel berm, in contrast to adjacent parts that rest on either steel or concrete beams elevated above ground level. At the Denali fault the beams are 14 m long and about 18 m apart over a pipeline distance of nearly 600 m (Péwé and Reger, 1983, p. 93-94). Between the pipe and the beams are special shoes that permit the pipe to move horizontally and vertically with respect to the ground.

Figure 6. Special design of the Trans-Alaska pipeline to accommodate surface faulting at the Denali fault. The part of the pipeline in the background, beyond the active fault zone, is elevated and has the normal above-ground design. The part of the pipeline in the fault zone (foreground) is at ground level and rests on steel or concrete beams that allow the pipe to move horizontally and vertically. The design fault displacements are 6.1 m strike shift and 1.5 m dip shift. The pipe is 1.22 m (48 in) in diameter. Photograph by 0. J. Ferrians, Jr., U.S. Geological Survey, September 19, 1977.

Special designs were used at two other fault crossings. Nearly 1,700 m of the pipeline lies in the McGinnis Glacier fault zone. The design analysis used the fault parameters given above. Design changes from the standard elevated configuration included substitution of friction supports for some anchor supports and addition of more bumper stops than usual. If the design faulting occurs, some of the supports are expected to behave plastically. For the 2,600-m crossing of the Donnely Dome fault, analysis using the fault parameters given above indicated that in the elevated configuration the pipe would accommodate the design fault displacements, although some supports may behave plastically.

For various nonseismic reasons the pipeline is buried rather than above ground in the 6-km segment where it obliquely crosses the Clearwater Lake fault identified in the early studies. Review of the design showed that the buried pipe could not safely resist the design fault displacement at the oblique angle at which the fault was crossed. Options at this point included the following: (1) make no changes but conform to some very severe requirements, including seismic monitoring of the fault, making provisions for rapid shutdown, and a site-specific contingency plan for oil-spill control; (2) reorient the pipeline so that the angle of intersection with the fault would be closer to 90°; or (3) conduct a detailed investigation to determine whether an active fault actually crosses the pipeline and, if so, exactly where (Williams, 1982, Appendix B). Option 3 was chosen, and a program that included geologic mapping of Quaternary deposits and land forms, logging of trenches, radiocarbon dating, and gravity and magnetic surveys was performed by the consulting firm that had done the original studies. The conclusion from the detailed studies was that the Clearwater Lake fault identified in the earlier studies did not represent an active fault and that no design for fault displacement was needed (Williams, 1982, Appendix B).

General Electric Test Reactor

The General Electric Test Reactor, located near Pleasanton, about 50 km east of San Francisco, California, was licensed in 1959 and was the first commercial reactor to be licensed in the U.S. Before being shut down, the facility was an important producer of medical radioisotopes. In 1977, during review of the geology and seismology related to renewal of the operating license, a new map was released by the U.S. Geological Survey. This map (Herd, 1977) shows the trace of the Verona fault about 60 m from the reactor, whereas an earlier map (Hall, 1958) shows the fault about 900 m from the reactor. After limited trenching and other studies were done, the Nuclear Regulatory Commission issued an order to put the reactor in a cold shutdown condition and show cause why the shutdown should not continue. Intensive investigations were carried out by the licensee, the Nuclear Regulatory Commission, and the U.S. Geological Survey. Among the stipulations agreed to by all directly involved parties was that the plant is located within a zone of tectonic faulting, the Verona fault zone (Atomic Safety and Licensing Board, 1982, p. 14). Two aspects of the studies relating to the plant were unusual. Probability analyses were used in evaluating the possibility of faulting beneath the reactor. These analyses were accepted with some reluctance by the staff of the Geosciences Branch of the Nuclear Regulatory Commission and by only two of the three members of the Atomic Safety and Licensing Board (1982). The other unusual feature was the licensee’s conclusion that should the design fault displacement (reverse oblique slip of 1 m) occur, it would be deflected around the reactor foundation. This analysis was accepted by the staff of the Geosciences Branch and, with reservations on the part of one member, by the Atomic Safety and Licensing Board (1982). To my knowledge, this is the first time that probability analyses and a fault-deflection proposal have been applied and accepted with regard to possible faulting under a nuclear reactor. The Atomic Safety and Licensing Board (1982) approved the restart of the reactor provided that specified changes were made, but the reactor has not been restarted. During the shutdown period of 1977 to 1982, when the possibility of faulting at the plant site was being investigated and hotly debated, the General Electric Company lost its medical isotope business to Canadian firms (Meehan, 1984, p. 127). Additional discussions of the impact of geological issues on the nuclear industry are given in James and Kiersch (Chapter 23, this volume).

Auburn Dam

The Auburn Dam, in the Sierran foothills 50 km northeast of Sacramento, California, was planned to be the world’s longest doubly curved thin-arch concrete dam, having a length of more than 1,200 m and a height of more than 200 m. The dam site is in an area of historically low seismicity, and although located within a regional fault zone, no active faults were known in the area. The foundation of the dam was being excavated in 1975 when a magnitude 5.7 (ML) earthquake accompanied by minor surface faulting occurred 68 km away, also in the Sierran foothills. This unexpected event led to detailed regional and local studies of the potential for faulting and earthquakes near the dam site (Packer and others, 1978). Catastrophic failure of the dam could result in great loss of life and property—one estimate placing the potential deaths at 260,000 (Rose, 1978)—and therefore the problem was reviewed by several agencies and consulting boards. Estimates of possible fault displacements at the site ranged up to 1 m. The

State of California recommended ". . . a design that would permit the structure to withstand a fault displacement of three-quarters of a foot.. ." (letter from H. D. Johnson, secretary for Resources, State of California, to C. D. Andrus, Secretary of the Interior, March 5, 1979). In a news release on July 30, 1979, the Secretary of the Interior announced that the Bureau of Reclamation would seek to develop such a design. Estimates of the cost of the project before it was put in abeyance range from $200 million (Wallace, 1986, p. 13) to $300 million (San Francisco Chronicle, 1979).

Other dams

Besides the Auburn Dam and the Sheffield and Lower San Fernando dams discussed above, which were affected by actual or potential earthquakes or faulting, several dams, all in California, have been modified because of the possibility of faulting in the foundations. During the planning stage for Morris Dam, east-northeast of Los Angeles (Fig. 7), a fault was discovered in the foundation bedrock at the dam site, and the design of the 75-m-high concrete dam was modified to include a special joint that would allow fault displacement. When the sediments overlying the bedrock fault were excavated during construction, they were found to be unfaulted, leading to the conclusion that the possibility of future faulting was slight; however, the special joint was retained when the dam was built in 1935 (Louderback, 1950; Legget, 1962, p. 515). The earth-fill, 37-m-high Coyote Dam, built across the Calaveras fault 30 km southeast of San Francisco in 1936, is designed to accommodate 6.1 m of horizontal and 1 m of vertical fault displacement (Louderback, 1937, 1950; Sherard and others, 1974). An earth dam built in 1891 across the San Andreas fault near Palmdale (Fig. 7) was completely reconstructed in 1969 because of the possibility of faulting. The new Palmdale Dam, of zoned-embankment type, was designed with the expectation that as much as 6.1 m of horizontal and 1 m of vertical fault displacement could occur (Sherard and others, 1974). The earth- and rock-fill Cedar Springs Dam (Fig. 7), 66 m high, was built over faults, considered active, that cross the site longitudinally. Vertical displacement in alluvium on one of the faults was as much as 1.5 m, but the amount of horizontal fault displacement, if any, could not be determined. Changes in the original design because of the faults included reduction in height, shifting of the axis, and major changes in the zonation of the dam (Sherard and others, 1974). The earth-fill, 47-m- high Los Angeles Dam (Fig. 7) was built in 1976 to replace the severely damaged Lower San Fernando Dam, described above. After exhaustive study, it was concluded that the dam site was within a zone of faults capable of future vertical displacements of 1 to 2.7 m at the time of a postulated local earthquake of about magnitude 7.5 (Yerkes and others, 1974; Wesson and others, 1974). Ground motions from the postulated earthquake and the estimates of potential surface faulting were incorporated in the design of the dam (Civil Engineering, 1978; Federal Disaster Assistance Administration, 1975, p. I-D- 14, I-D- 15). The design values for the earthquake ground motions and faulting were partly based on research on those topics stimulated by the investigations for the Trans-Alaska pipeline system and the Bodega Head nuclear reactor site, described above.

San Francisco sewer outfall

A sewer outfall extending into the ocean off San Francisco, California, had to cross the San Andreas fault (Gilbert and others, 1981; Murphy and Eisenberg, 1985). A design consideration was the possibility of as much as 5 or 6 m of horizontal and about 1 m of vertical fault displacement during a magnitude 8+ earthquake. Under the assumption that such a large seismic event probably will not occur during the 75-year design life of the outfall, the design philosophy was to accommodate smaller fault displacements but minimize damage and provide for easy repair should the larger displacements occur. For a distance of 366 m centered over the fault zone, special flexible joints were provided between the individual sections of the reinforced concrete pipe, which has an inside diameter of 3.7 m. Provision was made for access to the pipe and for diverting the sewage should the pipe be broken by faulting.

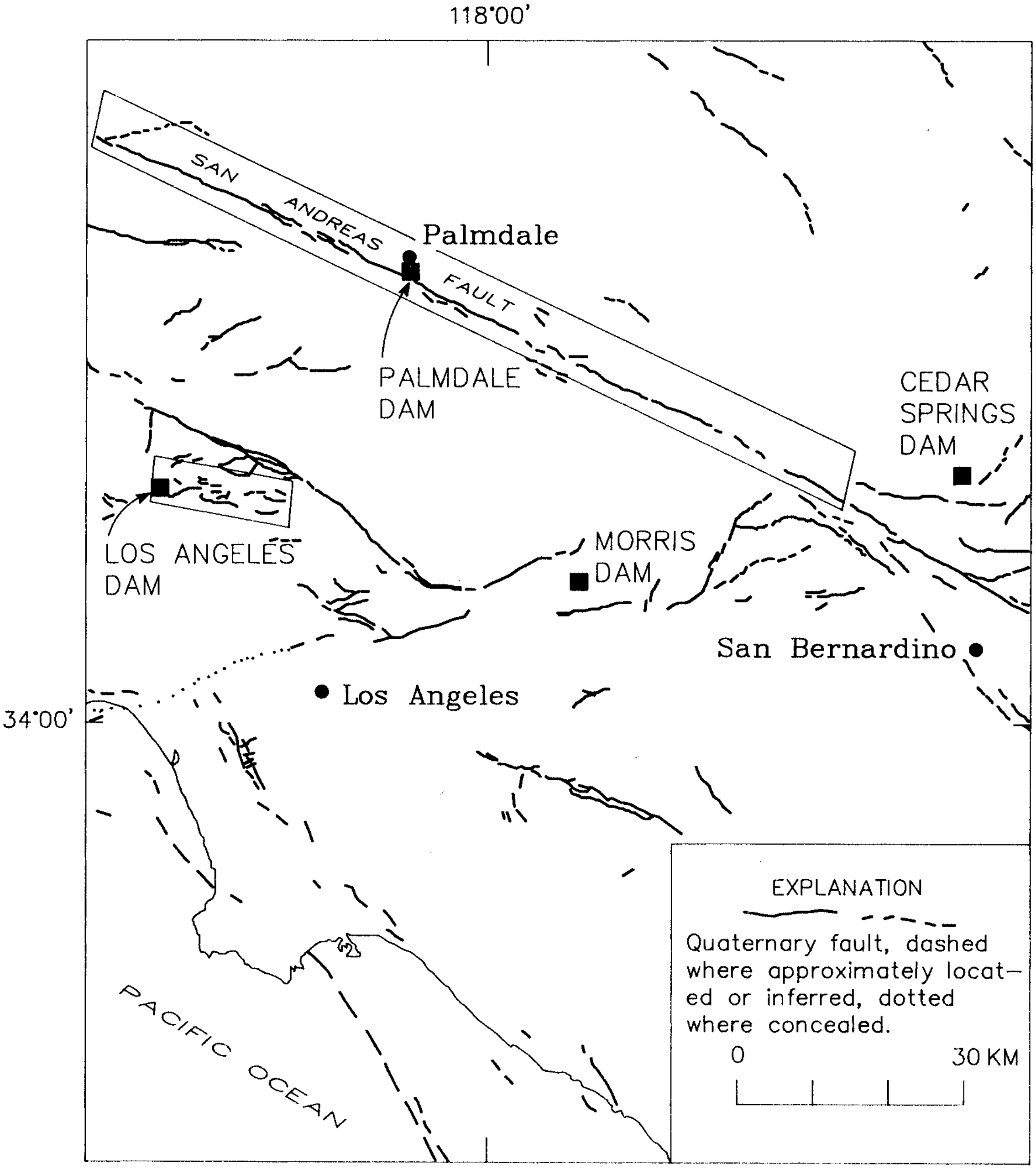

Figure 7. Map of part of southern California showing Quaternary faults and locations of four dams that have been designed to accommodate fault displacement. The reservoir behind Cedar Springs Dam is called Silverwood Lake. Fault traces from Jennings (1975). Coseismic surface faulting has occurred in historical time within the areas outlined by the two parallelograms.

RESEARCH NEEDS AND OUTLOOK

An American Society of Civil Engineers committee on the siting of nuclear facilities included among their conclusions the statement, ". . . definition of geologic and seismic characteristics of potential sites remains the area in greatest need of additional effort to reduce current conservatisms . . ." (Kruger, 1979, p. 498). This statement could be applied to other types of projects as well. The severe impact of actual or potential faulting and earthquakes on a wide variety of projects is apparent from the descriptions given herein. Clearly, the appraisals of the risks from faulting and earthquakes must be accurate to avoid costly overconservatism or underconservatism, and research leading to a better understanding of the process should continue. The following summary of some specific research needs is based on case histories summarized above, recommendations of a National Science Foundation workshop (Sitar and others, 1983), recommendations of a committee of the National Research Council (Wallace, 1986), and my experience.

New and improved techniques are needed for dating Quaternary materials and events. Accurate techniques are necessary to improve our knowledge of prehistoric tectonic events and their attendant earthquakes. Better dating techniques are also required for improvement in the evolving field of tectonic geomorphology, which can contribute much to the analysis of recent and current deformation. Probability analyses can be expected to play an increasing role in decisions regarding future risk from faulting and earthquakes; however, improvement is clearly needed in presentation to nonspecialists of the value, methods, assumptions, sensitivity to the assumptions, and limitations of probabilistic analyses. Particularly, such analyses should only be made with a thorough, qualified knowledge of the geological and geophysical environment.

The 'characteristic earthquake' model needs to be tested. It suggests that a given fault or fault segment will produce faulting and earthquakes of nearly the same size in successive events. Of great significance is the question of whether, at a particular site, several displacements of similar size can be followed by a much greater displacement.

Further research is needed on the interaction between an engineered structure and a propagating fault. In the 1972 Managua, Nicaragua, earthquake, strike-slip surface faulting of small displacement (about 17 cm, according to Niccum and others, 1976) was apparently deflected by an underground vault that was stronger than the slightly-to-strongly indurated sand and gravel in which it was embedded (Niccum and others, 1976). A laboratory-model study of a structure in a strike-slip fault produced a similar result (Duncan and Lefebvre, 1973). An analysis of the General Electric Test Reactor, described above, predicted that reverse oblique slip of 1 m will bypass the reactor. Additional research on this type of interaction is needed and should include the following: (1) the physical properties of the material surrounding or below the structure and the three-dimensional variation of those properties; (2) the type, amount of displacement, and rupture velocity of the faulting; and (3) the inertia and physical properties of the engineered structure. Better understanding of fault-structure interaction would be applicable to both existing and future projects.

Only a few inconclusive data are available regarding the absorption or dispersal of fault ruptures as they pass upward through unconsolidated materials or weak rock (Bonilla, 1970, p. 58-59). The phenomenon is important in at least two ways. One way is in determining the time of most recent displacement on a fault, such as the shaft fault at the Bodega Head reactor site. The second way is determining whether a fault in bedrock will propagate upward through thick, unconsolidated deposits in such a manner as to damage a structure near the ground surface. An analysis of the problem in connection with nuclear reactors was done by finite-element methods (Scott and Schoustra, 1974), and other laboratory and numerical studies (Roth and others, 1981a, 1981 b, 1982; Cole and Lade, 1984; Lade and others, 1984) are also applicable. More empirical, laboratory, and theoretical studies are needed.

None of the dams and other structures discussed above that have been designed to accommodate fault displacement have yet been tested by actual faulting. This fact emphasizes the need for research such as that outlined in the preceding two paragraphs.

Better ways are needed to distinguish marine and nonmarine terraces that have been relatively uplifted gradually (e.g., by folding or change in sea level) from those that have been uplifted suddenly by coseismic fault displacement. Sudden uplift can be assumed to be accompanied by earthquakes and tsunamis; furthermore, rapid uplift could have serious consequences such as shoaling of harbors or lifting the cooling-water intake of a nuclear reactor above water level.

The history of research in the field of engineering geology suggests what the future will bring. The historic pattern has been that a practical problem results in limited research that provides an immediate but commonly incomplete basis for a decision on the problem; frequently the initial research is followed by further research that provides better solutions to similar practical problems and at the same time contributes to the geological sciences. The field of engineering geology in the future, as in the past, will include research that both solves practical problems and contributes to an improved scientific understanding of geological and geophysical processes. Sponsorship and performance of the problem-oriented research will be done by both the public and private sectors of society.

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