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TECTONIC ACTIVITY IN CALIFORNIA AND ITS RELATION TO ENGINEERING GEOLOGY[1]

(*Fig. 1—4*)

Abstract: Engineering geologic conditions and problems in California are related to a number of interdependent factors, including climate, topography, distribution and behaviour of ground and surface water, stratigraphic and tectonic history, and rock type and condition. The most basic of these factors is tectonic activity, which has been extensive in California throughout its geologic history, for it has influenced each of the others to a greater or lesser degree. Uplift of the Sierra Nevada created a mountain range high enough that glaciers formed along its crest during Pleistocene time and a rain shadow developed on the arid eastern side; clearly much of the past and present climate of the Sierra Nevada and the desert to the east is directly attributable to past tectonic history. This rising mountain range was the source of material for the sedimentary rocks of the Jurassic and Cretaceous Great Valley sequence of California west of the Sierra. Farther west, the rising Coast Ranges rapidly eroded, shedding material into numerous smaller basins. Thrusting of the Franciscan rocks of the Coast Ranges eastward under the coeval Great Valley sequence has so crushed and sheared these rocks that their physical properties are drastically changed. Current tectonic activity causes severe earthquakes.

Резюме: Инженерно-геологические условия и проблемы Калифорнии зависят от целого ряда факторов — от климата, топографии, распределения и поведения грунтовых и поверхностных вод, стратиграфического и тектонического прошлого, а также от типа пород. Основным фактором является тектоническая активность которая была очень сильна в геологическом прошлом Калифорнии и влияла на все другие факторы. Вследствие поднятия Сьерра-Невада возникла горная цепь настолько высокая, что на ней во время плейстоцена могли обзоваться ледники а на восточной (засушливой) стороне зона без дождей. Эта горная цепь была областью сноса материала давшего отложения юры и мела. Дальше на запад поднимается цепь Кост Ренджс, которая была очень быстро снесена эрозией и материал перемещен во множество небольших бассейнов. Складчатость пород в цепи Кост Ренджс была причиной такого распада пород, что их физические свойства изменились. До сих пор продолжающаяся тектоническая активность области является причиной сильных землетрясений.

Many of the engineering geologic consequences of tectonic activity in the state are severe and obvious. Folding and fracturing of most of the rocks has made them more susceptible to weathering, erosion, and landsliding. The intense shearing of the Franciscan Formation, which underlies hundreds of square miles of the Coast Ranges of

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[1] There is a close analogy in engineering geological conditions between the West Carpathians and the mountainous regions in California, due to geological history, occurrence of similar rocks, and geomorphological conditions. Many young tectonical movements have a great influence on numerous phenomena and processes which play a decisive role in engineering geology: highly disturbed and sheared rocks; deep weathering; rapid erosion; widespread slope-sliding; slow tectonic creep along faults; and seismic hazards.

The many examples contained in this report (presented by D. H. Radbruch-Hall to the Slovak Geological Society in Bratislava) may encourage our geologists to study better similar phenomena also in the West Carpathians. (Editor's note).

California, has made it extremely slide-susceptible. Much of the area underlain by this formation has been recently uplifted; uplift continues to the present time, so that rapid downcutting by streams results in steep, unstable slopes. Landsliding in areas underlain by these rapidly eroding rocks in intense commonly producing landslides several square kilometers in extent. Rapid erosion is accompanied by the deposition of thick sequences of young, unconsolidated material with little strength. The many volcanic rocks throughout the state have contributed swelling clays to the younger rocks and the surficial deposits, which, as a result, shrink, swell, and are uncommonly susceptible to landsliding. Severe earthquakes in California pose many problems related to construction. Many of the active faults are moving constantly at very slow rates, causing damage to man-made structures.

Fig. 1. Physiographic provinces of California. After W a h r h a f t i g and B i r m a n (1965, p. 300).

It is convenient to discuss the tectonic activity and engineering geologic problems of California in relation to the physiographic provinces of the state. Each province, as shown on Figure 1, has distinctive rock types, geomorphology, climate, and tectonic history. Examples of engineering geologic problems and their relation to tectonic activity, particularly recent activity, are taken from three provinces that are quite different in these features: the Sierra Nevada, the northern Coast Ranges, and the southern Coast Ranges.

Sierra Nevada

The Sierra Nevada is a spectacular north — or northwest-trending range that borders central California on the northeast. Its southwest side rises rather gently eastward to culminate in a high crest that includes Mount Whitney, 4418 m in elevation; the eastern face drops precipitously to elevations of 1220—2135 m. The peaks of the Sierra Nevada receive about 200 cm of precipitation per year, mostly snow; the lower part of the eastern side, in the rain shadow of the range, is arid.

The Sierra Nevada contains a variety of rocks, including granitic and metamorphic; Paleozoic and Precambrian sedimentary; Tertiary and Quaternary sedimentary and volcanic; and lesser amounts of other rocks. The core of the range is a complex granitic batholith.

A Mesozoic geosyncline has been inferred in the area of the Sierra Nevada; after sedimentation, deformation, intrusion, and metamorphism, the geosyncline rose and was deeply eroded by the end of the Cretaceous Period (M. N. Christensen 1966). In early Tertiary time, highlands more than a thousand meters in elevation existed in the present summit area of the Sierra Nevada; the last major uplift that brought the range close to its present height probably began between 9 and 3 million years ago (M. N. Christensen 1966). The steep eastern scarp was formed later by downdropping of the area east of the range.

The southern end of the province includes the Tehachapi Mountains, which are somewhat different in structure from the Sierra Nevada. The Tehachapi Mountains are a horst of predominantly crystalline rocks that is partly bounded on the northwest side by the historically active White Wolf fault and on the southeast side by the Garlock fault, along which physiographic evidence of left-lateral movement is clearly visible, although it has not moved in historic time. Uplift on the southeast side apparently consisted largely of warping (J. P. Buwalda 1954). During Quaternary time, the Tehachapi block was uplifted as much as 1525 m relative to the Great Valley of California to the northwest.

Engineering geologic problems are relatively minor in most of the Sierra Nevada. Most of the rocks are not deeply weathered, partly because of recent glaciation. The metamorphic and granitic rocks are generally stable, although there are some avalanches, debris runs, and rockfalls, and some sheet spalling of the granites. A few landslides and earth flows form where volcanic rocks overlie softer material, and some volcanic mudflows are susceptible to intense erosion. Glacial deposits are not extensive; they consist largely of lake and morainal deposits in valleys and rock glaciers in old cirques. Transcontinental highways and railway lines that cross the Sierra Nevada have few problems of construction or maintenance except for a few landslides and rockfalls and the clearing of snow in the winter.

Engineering problems are more numerous in the Tehachapi Mountains at the south end of the province, where Tertiary sediments, as well as granitic rocks intensely

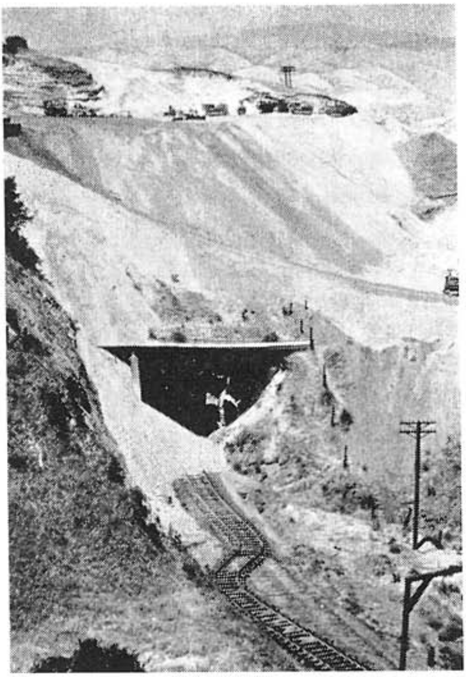

Fig. 2. Damage to tunnel and railroad resulting from the 1952 Arvin-Tehachapi earthquake.

sheared by recent fault movement, are prone to landsliding. An active segment of the San Andreas fault lies at the southwest end of the Tehachapi Mountains, which are also cut by several lesser faults. A steep, unstable scarp marks the course of the White Wolf fault; the fault itself is covered by massive slides that have formed along the steep face. One of California's great earthquakes — magnitude 7.6—7.7 — originated on the White Wolf fault in 1952; many slides blocked the roads, railroad lines were distorted, and tunnels were damaged (Fig. 2). There is no historic record of movement on the Garlock fault, but physiographic evidence of movement includes scarps, sag ponds, and the left-lateral offset of streams. This fault will undoubtedly move again.

The Tehachapi Mountains are part of a mountain barrier between the Great Valley of California, which extends northwestward for 640 km along the center of California, and the heavily populated Los Angeles area to the south. Highway routes, water supply lines, and many other lines of supply and communication extend across the Tehachapi Mountains, linking the Los Angeles area with regions to the south. Huge pipelines of the California Aqueduct that bring water more than 640 km from northern California to the Los Angeles area, cross the Tehachapi Mountains; the tunnels, pipelines, and pumping stations are now under construction. Special precautions have been taken where these lines cross the faults of the Tehachapi Mountains.

The choice had to be made between crossing the mountains at a low elevation by a 40 km tunnel, or crossing at a high elevation by pumping the water up to a series of short tunnels. The low-level tunnel would encounter gas, corrosive water, high temperatures, and sheared rocks of six major faults. A horizontal offset of 6 m was estimated as possible along the San Andreas fault; such an offset would crush a tunnel over a length of a hundred meters or more and might delay delivery of water for a long time while the tunnel was being repaired. A high route could avoid crossing major faults by tunnels so that the pipeline would not be seriously damaged by movement on any of the faults, but would involve high-cost pumping to lift 116 cubic meters per second of flow a height of 587 m. The high route was selected in order to avoid possible damage and stoppage of water supply in the event of a major earthquake.

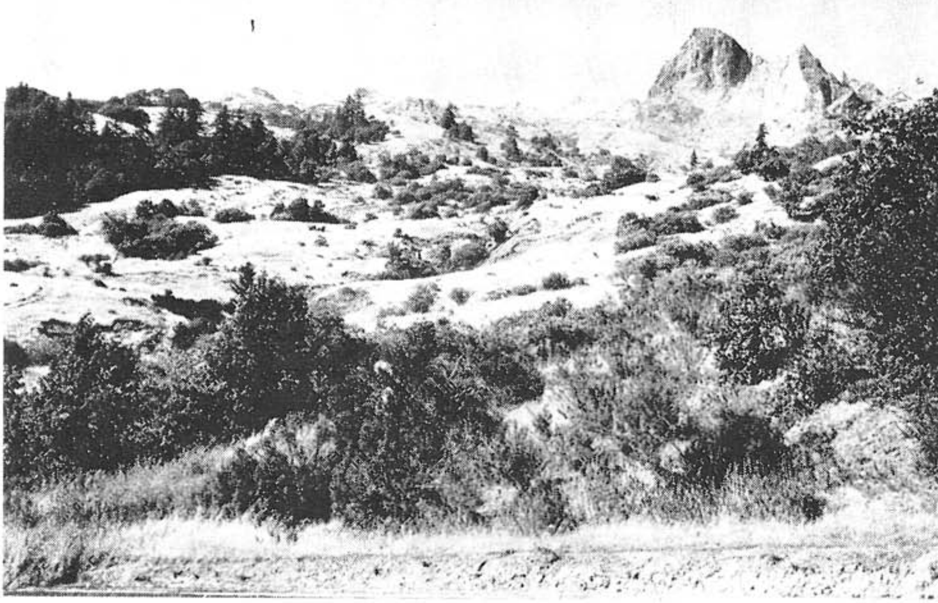

Fig. 3. Typical landslide topography in the northern Coast Ranges of California.

Northern Coast Ranges

The northern Coast Ranges lie along the Pacific Coast, extending northwestward from San Francisco Bay nearly to the northern California border. The predominant geologic unit is the Jurassic and Cretaceous Franciscan Formation; Mesozoic sedimentary rocks, Tertiary and Quaternary sedimentary and volcanic rocks, serpentinite, and other types of metamorphic rocks are represented. Many of these rocks have been badly sheared and contorted by tectonic disturbances; others are poorly consolidated.

The most slide-prone area in the state is in Franciscan rocks of this province. Landslides are abundant in intensely sheared sandstones and shales of the Franciscan Formation, which are commonly mixed with exotic blocks of more resistant greenstone, chert, and metamorphic rocks of various kinds. Landslides several square kilometers in extent are common (fig. 3). When seen from the air, the entire region underlain by this particular rock unit gives an impression of plastic movement, sheared rocks flowing downhill around the larger protruding exotic blocks to form a soft, creeping landscape.

These rocks have been likened to the argille scagliosa of Italy's Appenines (B. M. Page 1966) and the "colored mélange" of the Alps, the Himalayas, and Iran (A. Gannsser 1964); they somewhat resemble the Klippen Belt of the Slovak West Carpathians in physical characteristics and appearance if not in origin.

The origin of the Franciscan Formation is currently a matter of active study and debate among geologists working in California, although there is little doubt that at least part of its distinctive character is due to the intense shearing of relatively incompetent shales and interbedded sandstone, probably as the result of large-scale thrusting (E. H. Bailey — W. P. Irwin — D. L. Jones 1964; R. D. Jr. Brown 1964; E. H. Bailey — M. C. Blake 1969). The eugeosynclinal assemblage of Franciscan rocks was probably deposited on the oceanic crust, west of a coeval noneugeosynclinal succession of sandstone and shale. The Franciscan rocks are believed to have been thrust under the sequence that lies to the east as a result of continentward sea-floor spreading, with the deformation proceeding with deposition (Late Jurassic to Late Cretaceous). Subsequent strike-slip and dip-slip movement on the northwest-trending faults of the San Andreas system have cut the rocks of the coastal area into slivers (E. H. Bailey — M. C. Blake 1969). The northern Coast Ranges have been uplifted since late Pliocene time; deformation has affected the ranges throughout the Quaternary (C. Wahrhaftig — J. H. Birman 1965).

The type and abundance of landslides in the soft, sheared rocks of the Franciscan Formation make it a subject of intense interest to engineering geologists and engineers, especially as it occupies such a large part of the northern Coast Ranges. If engineered structures are contemplated in an area underlain by the incoherent part of the Franciscan Formation, construction and maintenance difficulties due to landsliding can be anticipated. There has not been much urban development in the northern Coast Ranges, where this type of rock is predominant, but suburbs of San Francisco are now extending northward into these landslide areas, and other engineering works, such as highways, bridges, railroads, dams, and reservoirs are being built there with increasing frequency.

A dam and reservoir in this type of geologic terrane was planned as part of the California Water Project. Geologists of the California Department of Water Resources who studied landslides in the area of the proposed reservoir learned that some of the slides are nearly 61m deep and may move as much as 6m per year. One quarter of the storage capacity of the reservoir could be lost due to sliding of rock and soil into the reservoir during its 100-year economic life (M. E. Huffmann 1969). The dam and reservoir have not been constructed.

Southern Coast Ranges

The southern Coast Ranges lie between the Pacific Ocean on the west and the Great Valley on the east and extend from San Francisco Bay southeastward almost to the city of Santa Barbara in southern California. The province consists of a number of complex ranges and basins underlain by a great variety of rocks, including granite, Franciscan rocks, Tertiary sedimentary and volcanic rocks, and poorly consolidated Quaternary deposits. The rocks are folded and faulted, and the province is sliced by the historically active northwest-trending San Andreas fault, along which extensive right-lateral displacement has accured. Relative uplift of mountains and basins has taken place throughout the past 2 or 3 million years (M. N. Christensen 1965). Erosion is rapid, slopes are dissected by numerous steep-sided canyons and ravines, and landslides in all types of rocks are abundant. This province includes the most heavily built-up parts of the San Francisco Bay area.

The danger of damage from earthquakes is ever present throughout California, but awareness of it is particularly acute in the highly urbanized San Francisco Bay region. This region is cut by several active faults of the San Andreas system on which strong earthquakes have originated in historic time. The most severe historic eartquakes in this area were the shock of 1906 on the San Andreas fault and the 1836 and 1868 quakes on the Hayward fault. The 1906 quake is well known because of the extensive

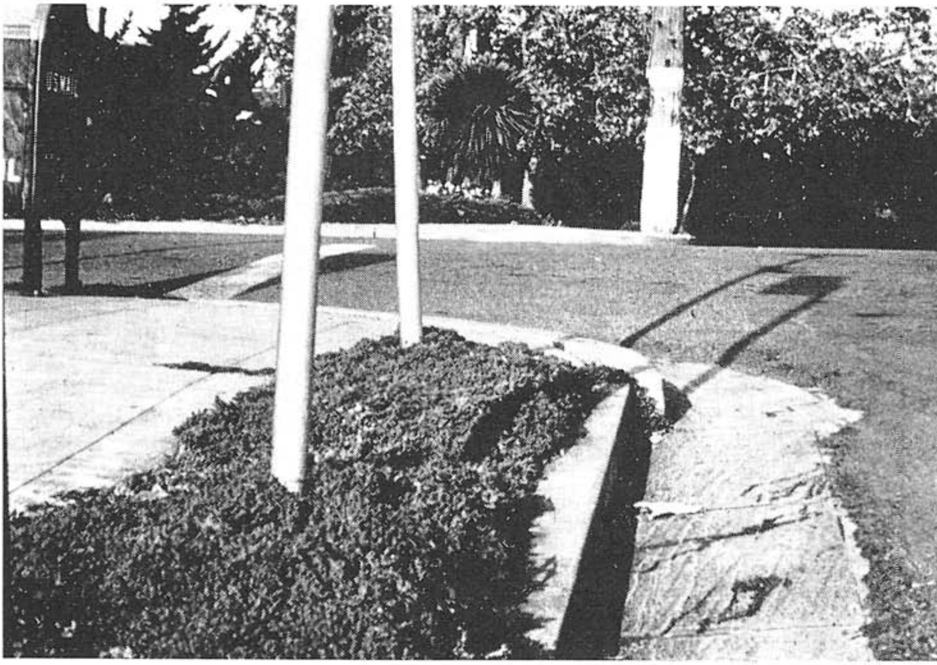

Fig. 4. Damage to a curb in the city of Hayward due to right-lateral tectonic creep along the Hayward fault.

damage to the city of San Francisco. Numerous lesser quakes have occurred along both the San Andreas and Hayward faults during historic time as well as along the Calaveras and other faults of the San Andreas system. A major earthquake comparable to the 1906 quake originated on the San Andreas fault in the southern part of the Southern Coast Ranges province in 1857, but it is less well known because the area was sparsely settled and there was little damage to the works of man.

Surface rupture of the ground took place at the time of all three of the major earthquakes in the San Francisco Bay area. For the 1836 quake, very little information regarding the nature of the rupture is available, as the area was sparsely populated at that time. Right-lateral movement of approximately 1 meter on the Hayward fault was reported for the 1868 quake, and right-lateral movement of 6 meters was recorded on the San Andreas fault in 1906.

Not only has surface rupture occurred during major earthquakes, but slow tectonic creep not accompanied by felt earthquakes is also taking place along active faults in this area. Tectonic creep on the San Andreas fault was first recognized in 1956, when fractures were seen in a winery building near Hollister, south of San Francisco Bay, that could not be explained in any conventional way. The winery lies across the San Andreas fault. Continuous measurement of the movement of walls and floors on either side of the cracks in the winery have shown that the northeast side of the building is moving southeast relative to the southwest side at the rate of about 1.25 cm per year (K. V. Steinbrugge — E. G. Zacher 1960).

In 1960 it was recognized that damage to a storage building on the Hayward fault was to creep along the fault. In 1965 other structures, including railroads, water tunnels, streets (fig. 4), and buildings along the Hayward fault were found to be damaged by the same kind of movement (M. G. Bonilla 1966; D. H. Radbruch — M. G. Bonilla et al. 1966; D. H. Radbruch 1967). Similar tectonic creep has since been recognized on other faults in California.

The greatest damage to structures in a seismically active area is caused not by surface rupture at the time of an earthquake or slow tectonic creep but by shaking. It is well known that shaking can be severe in soft, saturated sediments. During the 1906 earthquake, damage was most severe on artificial fill overlying muds deposited around the edge of San Francisco Bay. Such fill areas are extensive in the San Francisco Bay area.

Damage to structures can be caused by other effects of earthquakes such as cracking and settling of the ground not associated with actual fault rupture and extensive landsliding.

Many engineering problems arise in the development of a large urban area, such as the San Francisco Bay region, which is so seismically active. Not only buildings, but pipelines, roads, bridges, railways, and communication lines lie across the faults. The exact location of many of the faults in the San Francisco Bay area was only recently established and shown on published maps; prior to that time, many engineering structures were built along fault zones. Now that the location and characteristics of the faults are recognized, construction along fauls is being regulated by ordinances. Additional detailed mapping of the faults is now being done and seismic studies such as the effects of local geology on ground motion and monitoring of creep are being made. These studies will enable more precise definition of the fault zones and the preparation of more effective ordinances to regulate the type and location of construction in this seismically active rapidly developing area.

Many additional examples could be cited to illustrate the great influence of both past and present tectonic activity on engineering geologic conditions and problems in California. Many of these conditions and problems are being studied by geologists and seismologists of the federal, state, county, and city governments, universities, and private industry. The studies range from research on the mechanism of earthquakes and seismic response of earth materials to mapping specific construction sites. The need for studies will increase in the future as construction and development continue within the state.

REFERENCES

ARNOLD, A. B. 1969: The California Aqueduct in southern California, in Lung, Richard and Proctor, Richard, eds., Engineering geology in southern California, Spec. Pub. of Los Angeles Section, Assoc. Eng. Geol., p. 57—61.

BAILEY, E. H. — IRWIN, W. P. — JONES, D. L. 1964: Franciscan and related rocks and their significance in the geology of western California. California Div. Mines and Geology Bull. 183, 177 p.

BAILEY, E. H. — and BLAKE, M. C. Jr. 1969: Tektonischeskoe razvitie zapadnoj Kalifornii v pozdnem Mezozoe (Tectonic development of western California during the late Mesozoic): Geotektonika, pt. 3, p. 17—30; pt. 4, p. 23—34. (In Russian).

BONILLA, M. G. 1966: Deformation of railroad tracks by slippage on the Hayward fault in the Niles District of Fremont, California. Seismol. Soc. America Bull., v. 56, no. 2, p. 281—289.

BROWN, R. D. Jr. 1964: Thrust fault relations in the northern Coast Ranges, California. Art. 123 in U. S. Geol. Survey Prof. Paper 475-D, p. D7-D13.

BUWALDA, J. P. 1954: Geology of the Tehachapi Mountains in (Pt.) 9 Jahns, R. H., ed.,

Geology of southern California, chapter II. Geology of the natural provinces. California Div. Mines Bull. 170, p. 131—142.
CHRISTENSEN, M. N. 1965: Late Cenozoic deformation in the central Coast Ranges of California. Geol. Soc. America Bull., v. 76, p. 1105—1124.
CHRISTENSEN, M. N. 1966: Late Cenozoic crustal movements in the Sierra Nevada of California. Geol. Soc. America Bull., v. 77, p. 163—182.
GANSSER, A. 1964: Geology of the Himalayas. Interscience Publishers. New York, 289 p.
HUFFMAN, M. E. 1969: Geologic investigation of landslides along the Middle Fork Eel River, California (abst.): Geol. Soc. America, Abstracts with Programs, part 7, p. 111—112 (Renumbered v. 1, no. 7).
PAGE, B. M. 1966: Geology of the Coast Ranges of California, in Bailey, E. H. (ed.), Geology of northern California. California Div. Mines and Geology Bull. 190, p. 255—276.
RADBRUCH, D. H. 1967: Approximate location of fault traces and historic surface ruptures within the Hayward fault zone between San Pablo and Warm Springs, California: U. S. Geol. Survey Map I—522.
RADBRUCH, D. H. — BONILLA, M. G. et al. 1966: Tectonic creep in the Hayward fault zone, California. U. S. Geol. Survey Circ. 525, 13 p.
STEINBRUGGE, K. V. — ZACHER, E. G. 1960: Creep on the San Andreas fault. Seismol. Soc. America Bull., v. 50, no. 3, p. 389—415.
WAHRHAFTIG, C. — BIRMAN, J. H. 1965: The Quaternary of the Pacific mountain system in California, in The Quaternary of the United States a riew volume for the VII. Congress Inst. Assoc. for Quaternary Research, Princeton Univ. Press, p. 299—340.

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