SITE FEASIBILITY OF STANFORD’S PROPOSED 2-MILE LINEAR ELECTRON ACCELERATOR

By

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ERRATA SHEET

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Page 4, paragraph 2, should read:

2. The proposed research requires both a main test building and an exterior target area. The test building will measure 400' x 500', by 100' high, with floor foundation suitable for supporting heavy equipment. The contemplated building will consist of a steel framework of sufficient strength to support heavy overhead crane loads, and will be covered by asbestos siding or similar material. The point loading conditions demand rigid bedrock foundation if at all possible. Radiation shielding within the building will be provided around individual targets, or more generally if and when needed. The exterior target areas need only be reasonably level with sound soil or rock foundation.
Professor E. L. Ginzton, Director
Microwave Laboratory
Stanford University
Stanford, California

Dear Dr. Ginzton:

Presented herewith is our report on the site feasibility of the proposed linear accelerator based on information acquired to date, including documentation where possible.

It is our considered opinion that with respect to geographic location, topography, relative construction costs, and natural hazards, the proposed site is a feasible location for the planned accelerator.

Very truly yours,

Frank W. Atchley

Robert O. Dobbs
RESEARCH ASSOCIATES
(Geologists)
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INTRODUCTION

The purpose of this report is to assemble the information acquired to date concerning the feasibility of the Stanford site for the proposed 2-mile linear electron accelerator. The report is based on extensive review of the literature, photo-geologic interpretation, previous field mapping, discussion with eminent authorities in the fields of Seismology and Earthquake Engineering, and personal experience.

The evidence assembled to date clearly indicates that the proposed site is a feasible location for the construction of the linear accelerator. However, further detailed work, including mapping, soil and rock testing, subsurface drilling, and bulldozer exploration will be needed in order to establish the specific project alignment and foundation conditions for engineering design. In addition, in order to establish engineering safety factors that are commensurate with reasonable risk, eminent authorities in the fields of Seismology, such as Dr. Perry Byerly, University of California, and of Earthquake Engineering, such as Dr. George W. Housner, California Institute of Technology, will be consulted.
SUMMARY AND CONCLUSIONS

The study of site feasibility for a project such as the proposed linear accelerator requires careful consideration of project objectives, geographic location, topographic situation, and specific geologic conditions with respect to possible prohibitive construction costs, and hazards which could impair the usefulness of the project. Evaluation of these factors leads to the following conclusions:

1. The proposed site provides a very favorable geographic location close to related research activities at Stanford University and available supply, power, and scientific manpower sources.

2. The project requirements of tunnel length, tunnel cover, desirable side portal, adequate research working area, and sound stable foundations are all provided by the proposed site. The project area is on available Stanford land.

3. The geology of the site does not offer construction hazards or tunneling conditions which would significantly alter conventional design practices or tunneling methods, which factors together determine construction costs. The site has been examined by the Utah Construction Company, Bechtel Corporation, and Kaiser Engineers, and independently they reached the conclusion that the site was a feasible location for the proposed project.

4. Earthquakes in the San Francisco Bay Area are a recognized hazard. However, overwhelming empirical evidence proves that, although an area is hazardous, a minimum of danger exists to properly designed structures located on or in bedrock foundations. In the San Francisco Region there are mountain tunnels, a submarine tunnel, numerous skyscrapers, and the Bay Bridges, all of which
are earthquake-proof structures. The problem is merely a matter of engineering design and selection of best possible foundations.

5. Earthquake damage to tunnels rarely occurs. When damage does occur, it is only to improperly designed, poorly supported tunnels, or is in areas of incompetent rock in steep mountainous terrain. Even then damage occurs only when the tunnel is crossed by an active fault or is located in the epicentral area of the earthquake. The proposed tunnel will be specifically designed to resist earthquakes and will be driven in relatively competent rock in an area of gentle topography. No known active faults cross the proposed tunnel site, which is located 4 miles from the nearest zone of known epicenters along the San Andreas Fault. Therefore, we believe that there is a negligible risk involved in building the linear accelerator at the proposed site.
SITE REQUIREMENTS

The structures required to house the proposed linear accelerator are described in Stanford's initial proposal of April, 1957. However, at that time the desired site requirements of the proposed structures had not been defined, particularly the requirements which would insure optimum operating conditions. These requirements are summarized below. It may be said that the requirements demand careful geological evaluation, and dictate that the site have particular topography.

1. The principal structures will be two parallel level tunnels, 10 and 24 feet in diameter and 10,000 feet long. When completed, the tunnels will be in 24-hour continuous use, with personnel in the larger tunnel at all times. The continuous use, presence of personnel, and type of equipment demand particularly safe tunnels. There must be suitable tunnel access for personnel, equipment, ventilation, etc., and a centrally located side portal if at all possible. There must be adequate cover over the tunnel to insure safe radiation shielding.

2. The accelerator target will be housed in a radiation-proof structure which measures 400 feet by 500 feet, with 8-10 foot thick walls approximately 100 feet high. This structure should have particularly sound, rigid bedrock foundations, if at all possible.

3. Pinpoint target accuracy with deviations of one inch per year or five inches over a period of years is desired for operating convenience. This requirement does not raise construction problems, but does dictate stable foundations for the target building and the accelerator tunnel. It should be emphasized, however,
that the degree of stability stated above is desirable but not
critical and that deviation up to five feet can be tolerated.

4. There must be adequate working space in the target area for
present and future experimental purposes. Ideally, the target
area should be enclosed in an amphitheater valley, with steep
natural hillsides for horizontal radiation shielding.
SITE FEASIBILITY FACTORS

The proposed project site is on available Stanford land which has been reserved for this purpose. The site is located only two miles south of related research activity at Stanford University, and geographically located where power and supplies, as well as scientific manpower to plan, direct, and staff the project are available.

The topography of the site affords a suitable location for level, 10,000-foot tunnels with open portals on either end and a centrally located side portal. The target area, with nominal excavation, will provide adequate working space for all future needs and the excavation will insure sound bedrock foundation for the target building. The excavation also provides hillside radiation shielding. In short, from the point of view of location and topography, the proposed site appears ideally suited for the project. There yet remains the question of geological feasibility of the site.

Investigation of geological feasibility of tunnel sites may be resolved to specific questions concerning possible prohibitive construction costs, and hazards that could impair the usefulness of the tunnel following its completion. Satisfactory answers require careful consideration of regional and local geology, and knowledge of project objectives, engineering design limitations, and construction costs.

The relative importance of the geological factors which affect the ultimate construction costs, including corrective and preventive measures for hazards that are known to be present, can vary greatly. For example, there is general agreement that with sufficient justification a safe usable tunnel can be designed to counteract practically any unfavorable geological
situation, from running quicksand and underground rivers to solid granite. The problem lies in detecting and defining the hazards that are involved and the working conditions which will be encountered during construction.

Construction Costs

Tunnel construction costs may vary tremendously, depending on specific geologic conditions. It is necessary to assess in dollars and cents the significance of rock character and geologic structure with respect to tunnel diameter, excavation difficulties, and roof support requirements. It is necessary to appraise the portal areas with regard to access, working area, muck disposal, storage, and availability of power. Necessary contingencies must be included for unexpected excavation and support difficulties and for extra pumping and ventilation in case groundwater, natural gas, or high temperatures are encountered.

In the present case, the project area has been examined by three recognized engineering construction firms, the Utah Construction Company, Bechtel Corporation, and Kaiser Engineers. For comparative purposes these firms considered different project alignments in the same general area and, in each case, reached the independent conclusion that the site was a feasible location for the proposed project. The three firms were requested to amplify and explain their respective conclusions for permanent record. Their summary conclusions are bound as Appendix E.

Tunnel Hazards

The major tunnel hazards, other than those which affect the tunnel design and construction costs, are limited to phenomena which could render
the tunnel unusable after its completion.

These hazards are summarized below. The seriousness of any one is a question of probability of occurrence, monetary value of interrupted operation, and repair costs:

1. Tunnel collapse or failure due to forces of gravity causing swelling or squeezing ground, or downward settlement of broken rock.
2. Major bedrock slides from causes other than earthquakes.
3. Fault displacement across the tunnel.
4. Major damage due to earthquakes.

Tunnel failure due to forces of gravity or bedrock slides is a consequence of inadequate exploration and/or improper design. These hazards can be eliminated. The hazards of fault displacement and major damage from earthquakes require more serious consideration and are discussed in later sections.

In the present case, there is the additional possibility of bedrock deformation in excess of the desired operating tolerances. However, this is more of an operational problem than a hazard which affects the feasibility of the site, and it will not be discussed in this report. The possibility of such crustal deformation exceeding the allowable tolerance of 5 feet in a distance of only 2 miles is extremely remote.
Earthquakes are caused by movements in the earth's crust. Minor earthquakes may be associated with volcanic activity or landslides, but all large earthquakes are caused by the movements of blocks of the crust along deep-seated fractures called faults. The destructive earthquakes are associated with movements along major faults and usually originate at depths of 10 to 25 miles below the surface (10)*.

The generally accepted mechanism of fault earthquakes is defined by the "elastic rebound theory" proposed by Reid in 1910 (11)*. According to this theory, the crustal blocks on opposite sides of an active fault are in continual motion. This movement causes bending or straining of the rocks within the blocks. When the accumulated strain exceeds the frictional resistance along the fault, a failure occurs and the rocks on opposite sides of the fault snap back to their original unstrained positions. This snapping action, and the rubbing due to differential movement of the rocks along the fault plane, generate the vibrations that constitute an earthquake. Aftershocks originate in the same way except that the strain of the rocks is accumulated quickly as a result of the movements along the master fault. The point on the surface of a fault plane at which active slipping first takes place is called the focus. The point on the surface of the earth immediately above the focus is termed the epicenter. These points may be determined instrumentally, but it should be realized that the energy release and intensity of shaking may be distributed along the entire active segment of the fault.

*Numbers in parenthesis refer to specific publication list in Appendix F.
The magnitude of an earthquake is an instrumentally determined quantity which was originally derived by Dr. C. F. Richter to measure the total released energy. The intensity of an earthquake varies with location and is a measure of the destructive power of the shaking. The various intensity scales are based on the arbitrary evaluation of the effects of an earthquake as defined by sensory observation and by the extent of damage to structures (10)*.

The two types of destructive vibrations resulting from earthquakes are longitudinal waves (P) and transverse waves (S). The P waves are the faster and radiate maximum energy along the plane of the fault. The slower S waves radiate maximum energy in a direction perpendicular to the fault plane (10)*. The destructive power of the wave motion depends on the amplitude, frequency, and duration of the vibrations, with the S waves generally being the most destructive. Close to the fault line the P waves may be extremely destructive, but their energy decreases rapidly away from the fault. For any given wave, the amplitude of ground vibration varies greatly with the type of surface material that is involved, and may be many times greater in alluvium than in solid bedrock. The intensity of shaking in water saturated alluvium may be 10 or 15 times as great as that in the underlying bedrock (see Appendix B).

Earthquakes may occur in any part of the world but the major destructive earthquakes are concentrated in two belts, one along the Mediterranean-Himalayan axis, and the other in the mountainous areas bordering the Pacific Ocean. The West Coast of the United States, and particularly California and

*Numbers in parenthesis refer to specific publication list in Appendix F.
Nevada, lie within this latter zone of activity. It has been estimated that 2\% of the earthquakes in the world and 95\% of those in the United States (not including Alaska) occur in California and Nevada (2)*.

At present, there is no way to predict accurately the time of occurrence or the magnitude of future earthquakes. According to Dr. Perry Byerly (personal communication, July 7, 1959), there is insufficient evidence in the historical record to support the theory of cyclical reoccurrence of earthquakes in any given locality. The recent occurrence of a strong earthquake in a given area may be evidence that dangerous accumulated strain has been released, but it is equal proof that the area affected is one in which strain has accumulated in the past and will probably accumulate in the future. In like manner, the historical absence of a severe earthquake in an area of known seismicity, and along the line of a known active fault, may be evidence of a dangerous strain build-up but it may also indicate that strain is not accumulating but is being constantly released by gradual fault movements. Future progress in seismology and geodesy will probably provide the solutions to these uncertainties. At the present time, however, the problem of predicting earthquakes, especially as it affects construction progress, must rest on the assumption that the future will resemble the past and preventive measures must be taken accordingly.

Types of Earthquake Damage

Damage during earthquakes may result either from the movements along the fault plane or from the vibrations associated with these movements.

*Numbers in parenthesis refer to specific publication list in Appendix F.
According to Dr. C. F. Richter, of the California Institute of Technology, throughout the World there are only about 20 instances of proven surface rupture of bedrock which can be correlated with known earthquakes (10)*. Such ruptures have occurred as features of only the most destructive earthquakes and then only along the traces of faults which may be recognized as having been active in recent geologic time. In the usual case, the actual movement along the fault dies out before the surface is reached. In cases when surface rupture does occur, damage will consist of rifting and offsetting of roads, fences, pipelines, tunnels, dams and other structures which cross the trace of the fault. Such damage is usually severe but it is easily avoided by locating structures away from the traces of known active faults.

The strong vibrations of earthquakes may directly cause damage or destruction to structures and equipment, or they may trigger a variety of secondary effects which may also eventually result in damage to the works of man. The usual secondary effects are landsliding, and in alluvium or filled ground, slumping, lurching, and formation of pressure ridges. These latter effects are distinct from bedrock rupture. Landslides may occur in areas with deep soil cover, weak broken or sheared rocks, steep topography, and water saturated material. They are caused by the force of gravity acting on an unstable mass and are merely triggered by the earthquake vibrations. Landslides may uncover or crush tunnels, block roads and streams, or cover buildings. Landslides generally occur in areas where past landsliding has left recognizable features. Such areas should be avoided as construction sites if at all possible.

*Numbers in parenthesis refer to specific publication list in Appendix F.
Severe earthquake shaking of deep alluvium or artificial fill, especially when these are water saturated, may cause differential settling or spontaneous liquefaction. These phenomena result in the formation of cracks, ridges, and depressions, and in the occurrence of slumping and earth flow. When large structures must be built on alluvium, expensive foundation preparation, such as piling and grouting, is necessary.

With an earthquake of given character and magnitude, the severity of vibration damage to a structure will depend primarily on three factors: 1) distance from the epicenter or from the active segment of the fault; 2) type of engineering structure; and 3) the geologic foundation on which the structure is built. Within the area of destructive intensity, the factor of distance is probably the least critical.

In general, the resistance to earthquake damage is greatest in well-designed structures of reinforced concrete and least in buildings of unsupported masonry. Modern earthquake-proof structures are designed to resist the horizontal accelerations caused by earth vibration. They often incorporate design features to dampen structural vibration frequencies and large structures may include provision for differential movement between their various sections during severe shaking (10) (8) (3)*.

From the standpoint of earthquake resistant construction, the best possible foundation is sound strong bedrock and the worst is water-saturated alluvium, with all gradations being found between these extremes. The importance of foundation is shown by the many recorded cases of only slight

*Numbers in parenthesis refer to specific publication list in Appendix F.
damage to relatively weak frame and masonry buildings built on bedrock when, in the same earthquake, stronger structures built on alluvium were seriously damaged or destroyed, even when the latter were at a greater distance from the fault (10) (8)*.

*Numbers in parenthesis refer to specific publication list in Appendix F.
Many of the major earthquakes of California occur along a belt of north-west trending faults which extends from the Imperial Valley to the Northern Coast Ranges. The San Francisco Bay Region is transected by several of these major fractures. The Hayward and Calaveras faults extend through the eastern part of the Bay Area and the San Andreas Fault runs diagonally across the San Francisco peninsula. There may be another large active fault buried under the sediments of the bay and the Santa Clara Valley. These faults extend deep into the crust of the earth and are major structural features which are independent of smaller local structures. It has been established by observation of offset fences, roads, streams, and ridge lines that the movements on these faults is essentially horizontal, with the block on the west side of the fault moving northward with respect to the block on the east side of the fault. These movements have been confirmed by repeated measurements by the United States Coast and Geodetic Survey but the exact rate of movement, although about 2 inches per year between points 40 to 50 miles apart, has not been determined accurately (15) (16)*.

There is continual seismic activity, most of it very minor, associated with the fault systems of the San Francisco Bay Region. The general area is recognized by Dr. Byerly (2)* as the seismically most active region in California and has been classified by Dr. Richter (12)* as the most hazardous earthquake area in the United States. This hazard is generally recognized, and major engineering structures in the Bay Area are designed to withstand the effects of strong earthquakes.

The extent of seismic activity in the Bay Area may be seen by examining the plot of epicenters bound in this report as Appendix A. The

*Numbers in parenthesis refer to specific publication list in Appendix F.
larger earthquakes are located near the major fault lines, but the minor activity is widespread and, in many cases, is not associated with fault lines that can be mapped at the surface. This record of epicenters reveals that the areas of greatest seismic activity are concentrated east of the Bay and in the Santa Clara Valley. The southern part of the San Francisco peninsula, within a radius 15 or 20 miles of the proposed tunnel site, was remarkably free of epicenters during the recorded period.

The two most recent major destructive earthquakes in the area occurred in 1868 and 1906 and were caused by movement on the Hayward and San Andreas Faults respectively. Since 1906 some damage over limited areas has been caused by smaller earthquakes such as the 1933 Miles earthquake, and the 1937 Berkeley earthquake, and the 1957 Daly City earthquake (6)*. Surface ruptures were observed only in the two major earthquakes and then only along the main fault trace. The 1906 earthquake was by far the most destructive. Widespread damage to structures occurred throughout the region, particularly at Santa Rosa, San Francisco, Stanford University and San Jose.

About half of the City of San Francisco was destroyed, but only 20% of the destruction was due to the earthquake. The remaining 80% resulted from the great fire which followed the earthquake. The subsequent analysis of structural damage revealed that most of the buildings which were severely damaged were poorly designed, poorly constructed, and built on deep water-saturated artificial fill. Buildings on the rocky hills suffered comparatively minor damage. Properly designed structures on alluvium, even when they were of masonry construction, resisted the earthquake successfully (8) (3)*.

*Numbers in parenthesis refer to specific publication list in Appendix F.
A distinctive feature of the 1906 earthquake was a 270-mile surface rupture along the trace of the San Andreas Fault, which offset many natural and man-made features. The maximum horizontal offset was 21 feet. Two brick-lined railroad tunnels, which crossed the fault in the Santa Cruz Mountains, were offset and partially destroyed. The intensity of the initial shock wave near the fault was sufficiently severe to uproot oak trees and snap the tops off redwoods (8)*.

Stanford University is located 4 1/2 miles from the San Andreas Fault. Most of the buildings were of unsupported masonry construction and were built on fairly deep natural alluvium. The one- and two-story buildings were scarcely affected, but the arcades and several of the 3- and 4-story buildings suffered severe damage. However, in view of the unfavorable combination of masonry construction and alluvial foundation, it is remarkable that the majority of the buildings suffered only minor damage. Analysis of the Stanford damage revealed that most of the seriously damaged buildings were inadequately designed and poorly constructed even to the extent that inferior mortar had been used (8)*.

As a result of the 1906 earthquake, engineering designs have been developed which result in virtual earthquake-proof construction. Major engineering works built in the San Francisco Bay Region since 1906 include the Broadway and Twin Peaks tunnels, the Oakland-Alameda submarine tunnel, numerous tall buildings in San Francisco and Oakland, several tunnels of the Hetch-Hetchy aqueduct, and the Golden Gate, Oakland-Bay, and Richmond bridges.

*Numbers in parenthesis refer to specific publication list in Appendix F.
As stated previously, the accurate prediction of earthquakes is impossible with present knowledge. However, in the San Francisco Bay Region, with its history of earthquakes, seismic activity, and measurable crustal movement (2) (6) (15)*, it may be stated positively that major earthquakes will occur in the future, but that the time of occurrence is indeterminate. It may be assumed that the intensities of future earthquakes can be similar to, but will not exceed greatly, those of the 1906 earthquake.

*Numbers in parenthesis refer to specific publication list in Appendix F.
Review of the literature thus far has revealed only a few instances of earthquake damage to tunnels, principally railroad tunnels, affected during the 1906 San Francisco earthquake (8)* and the 1952 Kern County earthquakes (10)*. A more exhaustive survey of world-wide occurrence of earthquake damage to tunnels by C. M. Duke and D. J. Leeds, in an unpublished report for the second RAND symposium on protective construction, described two other cases. These involved damage to railroad tunnels in Japan during the 1923 Tokyo earthquake and the 1930 Tanna earthquake. In all of these cases, the damage occurred to unlined or poorly supported tunnels or to reinforced tunnels driven through incompetent broken rock in areas of steep topography. In each case either the active fault producing the earthquake passed across the tunnel, or the tunnel was located in the immediate epicentral area of the earthquake.

It is significant that there are several reported cases where major earthquake damage occurred at the surface, while miners working beneath the same area did not even notice the earthquake (3)*. It has been confirmed instrumentally that the amplitude or displacement of certain types of earthquake vibrations exhibit a marked decrease in depth. Depending on the types of materials involved, the ratio displacements may be as great as 10, or even 15.

In this respect, the summary and conclusions in the RAND Symposium report are pertinent to the appraisal of tunnel site feasibility. The text of the report is bound as Appendix B.

*Numbers in parenthesis refer to specific publication list in Appendix F.
A partial list of California water tunnels is bound as Appendix C. The list was obtained from the California State Department of Water Resources and includes only tunnels over 1,000 feet in length; it shows the tunnel name, location, bore, length, and date completed. A similar list of highway and railroad tunnels is being compiled.

There are over 100 major water tunnels in the state, totaling over 300 miles in length. Many of these tunnels are located in particularly hazardous earthquake areas, and have experienced strong earthquake vibrations. A number of the tunnels cross known active faults. It is significant that there are no known cases of failure in these water tunnels due to earthquakes.

The Los Angeles Metropolitan Water District owns and operates 142 tunnels totaling 43 miles in length; the Pacific Gas and Electric Company owns and operates 73 tunnels totaling 143 miles in length; and the San Francisco Metropolitan Water District owns and operates 34 tunnels totaling 76 miles in length. None of these companies have ever experienced significant earthquake damage in their tunnels (See Appendix B).

According to Mr. J. H. Turner, Chief Engineer and General Manager (personal communication, July 19, 1959), the San Francisco Water Department owns and operates 29 tunnels in the Bay Region, all within 50 miles of San Francisco. Many of these tunnels were built in the 1870's and are brick lined. These old tunnels went through the 1906 earthquake and suffered no damage, despite the fact that several were located only a short distance from the San Andreas Fault.
Regional Geology

The proposed accelerator site is located in the gently rolling foothills along the eastern side of the San Francisco peninsula. The surrounding area is characterized by northwest-trending topography which roughly reflects the structure and distribution of the underlying rocks. The major feature of the region is the San Andreas Rift Zone which lies approximately four miles southwest of the project site. This zone extends north-northwest diagonally across the San Francisco peninsula. The rocks and structures on opposite sides of the San Andreas Fault are distinctly different. Since no structures extend across the rift, only the geology east of the zone is described in this report.

The oldest rocks in the region are of Jurassic age and belong to the Franciscan Formation. This formation is a major unit in the Coast Ranges and is characterized by complex structures and diverse rock types. In the western part of the area these rocks are at or near the surface and in the eastern part of the area are overlain by folded sandstones, shales, limestones and lavas of Tertiary age. The tunnel will be driven through the latter rocks.

The major structural features in the western part of the area are strongly developed branching faults which diverge from the San Andreas Rift Zone and extend southeast across the area. The nearest of these large faults passes within 1½ miles of the project site. The Tertiary rocks in the eastern part of the area are moderately folded and are cut by faults which also trend northwest to southeast. These latter faults are less well developed and less continuous than the parallel faults to the west. The area is bounded on the east by the alluvial apron bordering San Francisco Bay.
Local Geology

The site geology was mapped by Stanford graduate students in 1956 under the supervision of Prof. B. M. Page. The mapping included earlier work by the writer, Frank Atchley. The geologic report is bound as Appendix D.

The principal rocks in the area consist of relatively weak shales and sandstones unconformably overlain by a local sequence of hard resistant basalts and weak volcanic agglomerates. These volcanics, in turn, are overlain by massive friable sandstones and lenses of hard sandy limestone. These rocks are of Tertiary age and, although tilted and folded, are relatively undeformed. They will provide better tunneling conditions than generally found elsewhere in the Coast Ranges, especially in the serpentines and deformed rocks of the Franciscan Formation.

There undoubtedly will be local troublesome sheared zones which are concealed, but generally speaking the rocks are sound and competent.

The over-all structure in the eastern half of the area is an eroded plunging anticline or dome which is locally modified by faulting. Structure in the western half of the area is essentially a tilted succession of strata dipping generally 35-60 degrees to the south and forming the south limb of the anticline. There are at least three discontinuous faults in the general area, but only one of these is known to cross the presently proposed tunnel line.

The tunnel line passes under the plunging end of the dome through more or less horizontal strata and then continues westward, crossing the tilted strata at an oblique angle. The principal rocks which will be encountered will be shales and sandstones.
APPRAISAL OF PROJECT HAZARDS

The proposed project will operate on a continuous 24-hour basis and there will be personnel at work in the control tunnel at all times. There will be expensive delicate equipment and rather heavy machinery located in the tunnels and target buildings. Once the accelerator is in operation, an interruption would involve large monetary loss.

The above features require particularly safe tunnels and necessitate concrete lining throughout. Adequate design measures will insure against the possibility of tunnel collapse, or rock slides in the portal areas. Thus, the only natural hazard which could interrupt the operation is major earthquake damage.

Earthquake damage may result from severe shaking or from fault displacement. Damage could occur to the tunnels, to the appurtenant buildings on the surface, or to equipment within these structures. The worst possible damage would be direct fault offset across the tunnel, with displacement greater than that which could be counteracted by adjusting the accelerator mountings. The next greatest hazard would be severe damage from toppling equipment, cracking of tunnel walls, local collapse, or structural damage at the surface.

Regarding the possibility of fault displacement, it has been shown that throughout the world there are only about 20 established cases of surface bedrock rupture accompanying an earthquake. Moreover, there have been no known instances of bedrock rupture except along the trace of recognized major active fault zones. In the Bay Area the only known bedrock ruptures have been along the Hayward Fault in the 1868 earthquake and along the San Andreas Fault in the 1906 earthquake. This evidence indicates that
there is but slight chance of a new fault break ever occurring in any
given small area, particularly if no active faults cross the area. In the
project area, mapping has revealed the presence of one fault crossing the
proposed tunnel line. There is no indication that movements have ever taken
place on these faults in historical or geologically recent time. Based
on this evidence, it appears that the hazard of fault displacement across
the tunnels is negligible.

Regarding the possibility of earthquake damage due to severe shaking,
it has been shown that the danger of damage to properly designed tunnels is
less than the danger of damage to structures on the surface. This is par-
ticularly so when the tunnels are not crossed by active faults. The most
likely hazard would be from toppling and shifting of machinery and equip-
ment within the tunnels. This danger can be minimized by the use of proper
mountings. The danger from rockslides and shifting rock, which could cause
collapse or cracking of the tunnel walls, is quite small at the proposed
site because of the presence of competent rock and gentle topography.

Minimizing the danger of earthquake damage to surface structures is a
matter of selecting the best possible foundations and then designing accord-
ingly. The present planned tunnel alignment is such that all critical
structures are founded on bedrock. For structure design, it is necessary
to estimate the horizontal acceleration that could result from an earth-
quake of expectable magnitude and establish a seismic factor of safety
that is commensurate with reasonable risk.
APPENDICES

A. MAP OF EARTHQUAKE EPICENTERS IN THE SAN FRANCISCO AREA

B. EFFECTS OF EARTHQUAKES ON TUNNELS, by D. M. Duke and D. J. Leeds

C. LIST OF CALIFORNIA WATER TUNNELS


E. ENGINEERING COMPANY SUMMARY REPORTS
   1. Utah Construction Company
   2. Bechtel Corporation
   3. Kaiser Engineers

F. SELECTED REFERENCES
Fig. 20. Map of San Francisco Bay area showing principal active faults (heavy black lines) and the epicenters of earthquakes that occurred during the periods 1930-41 and 1947-48. The intensity of the various shocks is shown by the epicenter symbols listed in the legend to the left of the map.
APPENDIX B

EFFECTS OF EARTHQUAKES ON TUNNELS

by C. M. Duke and D. J. Leeds*

(Manuscript draft without illustrations)

Introduction

An effort is made here to summarize and generalize the available information on earthquake damage to tunnels. Four reasonably well documented cases are presented, along with supporting and indirect evidence. The details of the failures and of the geology are less complete than is desirable, but the facts available appear to warrant several useful generalizations. The original sources cited may be consulted by those wishing to study the data in detail.

Experience in California and Japan

Central California, 1906. In the San Francisco earthquake of 1906 there were two damaged tunnels on the narrow-gage Southern Pacific Railroad between Los Gatos and Santa Cruz. The 6200-foot tunnel at Wright Station was crossed by the San Andreas fault and the 5700-foot tunnel directly to the south was also damaged, but to a somewhat lesser degree. Shaking at the surface over the tunnels was very intense, designated 10 on the Rossi-Forel scale. Damage to the tunnels themselves, Table I, consisted of the caving in of rock from the roof and sides, the breaking in flexure of upright timbers, and the upward heaving of rails and breaking of ties. Both tunnels were blocked at a number of points.

The tunnel at Wright Station suffered a 4.5 foot transverse horizontal offset where the fault cut it. See Fig. 1. This same movement wrecked the Morrell house which stood above the tunnel and on the fault. Tunnel damage was greatest around the offset and at the several locations where parallel fissures were in evidence.

* Respectively Professor of Engineering and Associate Research Engineer, University of California, Los Angeles.
The rocks in the Wright tunnel looked like sandstones and jaspers of Franciscan age.

Other tunnels on the Santa Cruz-Los Gatos line were undamaged, except for two cases of broken timbers. New tunnels under construction on the Bayshore line, in southern San Francisco, were uninjured.

Tokyo Area, Japan, 1923. The great 1923 earthquake damaged about 25 tunnels, Table II, in the vicinity of Tokyo, principally on the Izu and Boso peninsulas which are the mainland areas closest to the epicenter. The damage is attributed to shaking, as no case of faults intersecting the tunnels is known. Most of the tunnels were concrete or brick lined, with depth of cover, character of rock, length, and other features varying over a rather wide range. Particularly heavy tunnel damage occurred in the Odawara-Atami-Hakone region, which suffered the highest intensity of shaking. Beyond the isoseismal corresponding to approximately 50% of houses collapsed, tunnel damage apparently was insignificant.

Figures 2 through 6 illustrate the destruction in two selected cases. Damage varies from fractured portal masonry through cracked linings to cave-ins from roof and sides.

Tanna, Japan, 1930. The Tanna Tunnel, connecting Atami and Mishima, was under construction during the Izu earthquakes in 1930. The Tanna fault intersected one of the drain tunnels which extended ahead of the main tunnel heading, causing a transverse horizontal offset of 7.5 feet at a distance of about two feet beyond the main tunnel heading. See Figs. 7 and 8. The only damage to the tunnel was a few cracks in the walls. But in the village of Karuizawa, situated on the Tanna basin 160 meters above the tunnel, 55% of the dwellings were thrown down, and 40% of the houses were destroyed at the nearby villages of Tanna and Hata. Surface displacements on the fault occurred over a distance of 15 kilometers.
The Tanna basin is a lake deposit of sandy clay and boulders, about 40 meters deep, overlying andesite and agglomerate through which the tunnel passes.

Kern County, California, 1952. The Kern County earthquake of 1952 severely damaged four tunnels, Table III, on the Southern Pacific Railroad near Bealville, about 15 miles northwest of Tehachapi. This was the region of largest observed ground fractures associated with movement on the White Wolf fault. See Figures 9 and 10. In all, there were 15 tunnels between Bakersfield and Tehachapi, and those outside of but adjacent to the area of ground fractures suffered slightly, to the extent of opening of construction joints. The railroad in this area was built in about 1876, with timber lining in the tunnels. Reinforced concrete lining 12 to 24 inches thick was installed later, without removing the timber. Rock around the four damaged tunnels was a fairly easily excavated decomposed diorite.

Tunnel No. 3, originally 700 feet long, was heavily damaged at its Tehachapi end, 200 feet of which was daylighted after the quake. See Figs. 11 and 12. At one place the buckled rail extended under the concrete wall, indicating that the wall had raised sufficiently to permit this. While ground cracks were not found directly over No. 3, an active fault crossing the tunnel was found during daylighting.

Large surface cracks, Fig. 13, were found above No. 4, which was badly shattered, Fig. 14, and subsequently daylighted for its full length.

Tunnel No. 5 was very heavily damaged, Fig. 15, but was reconstructed without daylighting. Cracks and holes appeared in the ground above, and rock and soil from these cracks flowed into the tunnel.

Broken lining comprised the damage to No. 6, Fig. 16, which was daylighted. No substantial surface cracking was noted over this tunnel.
These tunnels were in the region of heaviest shaking, Modified Mercalli Intensity II, but clearly the extensive damage was primarily due to their location in the fault zone.

Fukui 1948 and Hokkaido 1952. At Kumasaka, north of Kanazu, the portal arches of a brick-lined tunnel were partially fractured in the 1948 Fukui earthquake. Also in this earthquake, a large concrete culvert was badly cracked at midlength. In the 1952 Hokkaido earthquake, minor cracking was induced in the walls of one concrete-lined and one brick-lined tunnel. Fault movement at the tunnels was not involved in the above cases.

Related Experience

Mines and Caves. During the Sonora earthquake of 1887, an engineer was in a mine at Tombstone, Arizona. He felt violent shaking and observed small rockfalls, but no collapsing, down to several hundred feet of depth. Most stopes were un-timbered. Damage on the surface consisted of falling plaster and chimneys, and shifting of engines on their foundations.

In another case, in mines at Butte and Barker, Montana, the 1925 earthquake was hardly noticed by those underground but was felt at the surface.

The August 22, 1952, Kern County aftershock was reported not to have been felt by a party in Crystal Cave, Sequoia, but to have been sharply felt by persons outside the cave.

There appears to be a possibility that rock bursts at Witwatersrand, South Africa, may be triggered by releases of energy at points in the mine complex away from the bursts.

Experience of California Agencies. Correspondence from W. M. Jaekle, Chief Engineer, Southern Pacific Company, reveals that, except for the 1906 and the 1952 cases, no damage or disturbance to Southern Pacific tunnels has been caused by earthquakes.
The Los Angeles Department of Water and Power operates the Owens Valley Aqueduct, which includes 142 tunnels totaling 43 miles in length. The Aqueduct was completed in 1911, and no tunnel damage due to earthquakes has occurred. The Elizabeth Tunnel, five miles long, crosses 3000 feet of the San Andreas rift zone at a depth of up to 1000 feet. It is inspected annually; no earthquake damage has been found to date.

The Pacific Gas and Electric Company has experienced no significant earthquake damage to tunnels in its 40 years of experience with 73 tunnels, unlined and concrete lined, totaling 119 miles in length.

The above experiences are significant in view of the fact that California has experienced severe earthquakes in 1915 (Imperial Valley), 1925 (Santa Barbara), 1933 (Long Beach), 1940 (El Centro), 1952 (Kern County), and 1954 (Western Nevada), in addition to the great earthquake of 1906.

**Effect of Depth below Surface.** Several Japanese investigators have measured small earthquake motion at some depth and simultaneously at the ground surface. Omori (1902) was the first to make such measurements. Nasu determined the ratios of displacements of 14 earthquakes at the surface above Tanna Tunnel and in the tunnel at 160 meters depth to be 4, 2, 1.5, 1.2 for periods 0.3, 1, 2, 5 seconds, respectively. The ground was lake deposits at the surface and andesite and agglomerate at depth. Saita and Suzuki found that the maximum acceleration at the surface of a 68-foot layer of alluvium was three to five times that at its base contact with diluvium. Inouye found that short-period waves (ripples) observed at the surface were largely absent at a 9-meter depth.

Carder of the U.S. Coast and Geodetic Survey recorded approximately equal amplitudes of microseisms at the surface and at 5000-foot depth in Homestake Mine. Microseisms were of four or five second period. In a later study, earthquake P-waves of one-second period were recorded at 300-foot depth with twice the
amplitude recorded at 5000-foot depth.

Recently, Kanai has made signal progress in this field. He operated seismographs at depths of 0, 150, 300, 450, and 600 meters in a copper mine in Hitachi and recorded a very large number of small earthquakes. The ground is paleozoic rock, with some weathering near the surface. The ratio of surface maximum displacement to that at 300 meters depth was about 6 at the mine and about 10 at a school 6 kilometers away on alluvium. Earthquakes whose average period of incoming waves was close to the free period of the surface layer caused these maximum ratios, but many earthquakes occurred for which the ratios were as small as one-third of the above. He also found that the period of the short-period waves (ripples), found on surface seismograms but not underground, corresponds to the predominant period of the surface layer; the ripples dominated the surface record when the incoming waves contained components with period equal to that of the ripples. These findings support quantitatively the theoretical amplification formulas of Sezawa and Kanai.

Qualitatively, these researches demonstrate experimentally the following effects of depth:

a. At short periods, surface displacements are larger than underground displacements.

b. The ratio of surface to underground displacement depends on the type of ground. It is greater for alluvium than for weathered rock. It may reach a value of at least 10.

c. For wave periods over one second, the ratio becomes comparatively small, approaching unity as the period increases.

d. There is a particular average period of incoming waves for which a given type of ground will provide a maximum ratio of surface to underground displacement. If the average period of incoming waves is not approximately equal to this particular period, the ratio will be materially smaller.
Generalizations

1. Severe tunnel damage appears to be inevitable when the tunnel is crossed by a fault or fault fissure which slips during the earthquake.

2. In tunnels away from fault breaks, severe damage may be done by shaking to linings and portals and to the surrounding rock, for tunnels in the epicentral region of strong earthquakes, where construction is of marginal quality. Substantial reinforced concrete lining has proved superior to plain concrete, masonry, brick, and timber in this regard.

3. Tunnels outside the epicentral region, and well constructed tunnels in this region but away from fault breaks, can be expected to suffer little or no damage in strong earthquakes.

4. While it would seem reasonable that competence of the surrounding rock would reduce the likelihood of damage due to shaking, inadequate comparative evidence is available on this point.

5. Within the usual range of destructive earthquake periods, intensity of shaking below ground is less severe than on the surface.

References

California Earthquake 1906


Special Committee, ASCE. The Effects of the San Francisco Earthquake of April 18th, 1906, on Engineering Constructions. Trans. ASCE, 59:208 (1907).

Tokyo Area 1923


Izu Earthquake 1930


Takahasi, R. Results of the precise levellings executed in the Tama railway tunnel and the movement along the slickenside that appeared in the tunnel. Bull. ERI 2:435-453 (1931).
Kern County Earthquake 1952


Fukui 1948 and Hokkaido 1952.


Mines

Effect of Depth on Amplitude

Inouye, Win. Comparison of Earth Shakings above Ground and Underground.


### APPENDIX C

**CALIFORNIA WATER TUNNELS**

The following list of California tunnels was obtained from the State Division of Water Resources. It is a partial list of water tunnels only, and the data is not complete. It is estimated there are approximately 50 highway and railroad tunnels in existence over 1,000 feet in length.

<table>
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<tr>
<th>NAME</th>
<th>LOCATION</th>
<th>DATE</th>
<th>BORE</th>
<th>LENGTH</th>
</tr>
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<tr>
<td>Gibralta Reservoir</td>
<td>nr Santa Barbara</td>
<td>prior 1942</td>
<td>7' x 9'</td>
<td>6 miles</td>
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<tr>
<td>Juneal Reservoir</td>
<td>nr Santa Barbara</td>
<td>prior 1942</td>
<td>7' x 9'</td>
<td>4 miles</td>
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<tr>
<td>Mono Crater</td>
<td>nr Leviing</td>
<td>1939</td>
<td>12'</td>
<td>59,813 ft.</td>
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<tr>
<td>Tecolote</td>
<td>nr Santa Barbara</td>
<td>1955</td>
<td>9'</td>
<td>33,557</td>
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<tr>
<td>Kerckhov</td>
<td>Fresno County</td>
<td>1920</td>
<td>18'</td>
<td>8,350</td>
</tr>
<tr>
<td>Pit No. 1</td>
<td>Shasta County</td>
<td>1922</td>
<td>16'</td>
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<tr>
<td>Pit No. 3</td>
<td></td>
<td>1925</td>
<td>22'</td>
<td>20,900</td>
</tr>
<tr>
<td>Pit 5 No. 5</td>
<td></td>
<td>1944</td>
<td>21'</td>
<td>5,837</td>
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<tr>
<td>Pit 5 No. 2</td>
<td></td>
<td>1944</td>
<td>21' x 21'</td>
<td>23,161</td>
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<td>Pit No. 4</td>
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<td>1954</td>
<td>21' x 21'</td>
<td>21,434</td>
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<td>Balch</td>
<td>Fresno County</td>
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<td>19,000</td>
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<td>Bucks Creek No. 1</td>
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<td>1925</td>
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<td>Bucks Diversion</td>
<td>Plumas County</td>
<td>1925</td>
<td>8'</td>
<td>5,750</td>
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<tr>
<td>Melones</td>
<td></td>
<td>1927</td>
<td>13.5'</td>
<td>4,960</td>
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<tr>
<td>Drum Canal No. 1</td>
<td>Nevada County</td>
<td>1928</td>
<td>10' x 14'</td>
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<tr>
<td>Tiger Conduit</td>
<td>Amador County</td>
<td>1932</td>
<td>10' x 11'</td>
<td>14,350</td>
</tr>
<tr>
<td>Stanislaus</td>
<td>Tuolumne County</td>
<td>1939</td>
<td>9.5' x 10'</td>
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</tr>
<tr>
<td>Colgate</td>
<td>Yuba County</td>
<td>1940</td>
<td>9' x 10'</td>
<td>24,674</td>
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<td>Oleum</td>
<td>Contra Costa</td>
<td>1942</td>
<td>10' x 11'</td>
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<td>Dutch Flat</td>
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<td>12' x 12'</td>
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<tr>
<td>Narrows</td>
<td>Nevada County</td>
<td>1943</td>
<td>11' x 14'</td>
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<tr>
<td>Tabaud</td>
<td></td>
<td>1948</td>
<td>14' x 14'</td>
<td>2,869</td>
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<tr>
<td>West Point</td>
<td>Amador County</td>
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<td>13' x 15'</td>
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<td>Electra</td>
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<td>1949</td>
<td>13' x 14'</td>
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<td>Cresta</td>
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<td>1949</td>
<td>23' x 26'</td>
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<td>Rock Creek</td>
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<td>1950</td>
<td>25' x 25'</td>
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<td>1952</td>
<td>10' x 12'</td>
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<td>1952</td>
<td>8.5' x 11'</td>
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<tr>
<td>Hendricks</td>
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<td>1953</td>
<td>7.5' x 8'</td>
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<tr>
<td>Wishon</td>
<td>Madera County</td>
<td>1956</td>
<td>15' x 15'</td>
<td>11,038</td>
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<td>Poe</td>
<td>Butte County</td>
<td>1958</td>
<td>24' x 24'</td>
<td>32,834</td>
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<td>Butte Valley</td>
<td>Lassen County</td>
<td>1958</td>
<td>15' x 15'</td>
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<tr>
<td>Caribou No. 2</td>
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<td>1958</td>
<td>15' x 15'</td>
<td>8,710</td>
</tr>
<tr>
<td>Hass</td>
<td>Fresno County</td>
<td>1958</td>
<td>13' x 13'</td>
<td>32,854</td>
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<td>Contra Costa No. 1</td>
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<td>1939</td>
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<td>Lake Merced</td>
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<td>San Pablo</td>
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<td>(??)</td>
<td>(??)</td>
<td>3 miles</td>
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<td>Claremont</td>
<td>(??)</td>
<td>(??)</td>
<td>(??)</td>
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<td>Walnut Creek</td>
<td>(??)</td>
<td>(??)</td>
<td>(??)</td>
<td>2,500 ft.</td>
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<td>25'</td>
<td>7 miles</td>
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<tr>
<td><strong>Colorado River Aqueduct System</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Colorado River</td>
<td>various</td>
<td>1939</td>
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<td>1 mile</td>
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<td>Coojan Basin</td>
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<td></td>
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<td>Whipple Mt.</td>
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<td>Iron Mt. East &amp; West (2)</td>
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<tr>
<td>Cocks Comb</td>
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<tr>
<td>East Eagle System (3)</td>
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<td>7</td>
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<td>Hayfield No. 1 &amp; 2 (2)</td>
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<td>Mesa Pass and Cochella Mt. System (10)</td>
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<td></td>
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<td>20</td>
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<td>Uvalde</td>
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<td></td>
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<td>8</td>
</tr>
<tr>
<td>San Jacinto</td>
<td></td>
<td></td>
<td></td>
<td>13</td>
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<tr>
<td><strong>San Diego Aqueduct System</strong></td>
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<td></td>
</tr>
<tr>
<td>Rainbow</td>
<td>various</td>
<td>1946</td>
<td>6' lined</td>
<td>4,700 ft.</td>
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<tr>
<td>Red Mountain</td>
<td></td>
<td>1949</td>
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<td>3,078</td>
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<tr>
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<td>1947</td>
<td></td>
<td>3,590</td>
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<td>Bowry</td>
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<td>Five Hill</td>
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<td>1946</td>
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<tr>
<td>San Vicente</td>
<td></td>
<td>1946</td>
<td></td>
<td>2,455</td>
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<td><strong>Hetch Hetchy Aqueduct System</strong></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Sierra Division</td>
<td>various</td>
<td>various</td>
<td>14' x 14'</td>
<td>99,264 ft.</td>
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<tr>
<td>(essentially one tunnel with short gaps)</td>
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<td></td>
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<td></td>
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<tr>
<td>Coast Division</td>
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<td>14' x 14'</td>
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<td>150,480</td>
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<td>(essentially one tunnel with short gaps)</td>
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<td></td>
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<td><strong>Mammoth Pool Aqueduct System</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Florence</td>
<td>various</td>
<td>prior 1930</td>
<td>15' x 15'</td>
<td>13 miles</td>
</tr>
<tr>
<td>Florence Lake No. 2</td>
<td></td>
<td></td>
<td>21'</td>
<td>67,634 ft.</td>
</tr>
<tr>
<td>Big Creek</td>
<td></td>
<td></td>
<td>24'</td>
<td>(?)</td>
</tr>
<tr>
<td>Mammoth</td>
<td></td>
<td></td>
<td>9'</td>
<td>3,008</td>
</tr>
<tr>
<td><strong>Owens Valley Aqueduct System</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 tunnels</td>
<td>(?)</td>
<td>(?)</td>
<td>12'</td>
<td>55,984 ft.</td>
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APPENDIX D

ENGINEERING GEOLOGY OF THE
PROPOSED SITE OF PROJECT "M"
STANFORD, CALIFORNIA

by H. C. Langerfeldt and L. W. Vigrass
under supervision of
Dr. B. M. Page, Stanford University

December, 1956
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<td>D-3</td>
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<td>Los Trancos formation</td>
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<td>Structure</td>
<td>D-5</td>
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<td>Engineering properties of the rocks</td>
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<td>Excavation</td>
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<td>Rock breakage</td>
<td>D-6</td>
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<td>Tunnel support</td>
<td>D-6</td>
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<td>Slopes of open cuts</td>
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ENGINEERING GEOLOGY OF THE
PROPOSED SITE OF PROJECT "M"
STANFORD, CALIFORNIA

SUMMARY AND RECOMMENDATIONS

In the area proposed as a site for Project "M", Eocene sandstone, mudstone and shale dip steeply southwesterly and are bounded to the west, south and east by more gently dipping miocene basalt, fragmental volcanic rock, limestone, sandstone and minor shale. Several faults, showing no evidence of recent movement, cut across this semi-domal structure.

From a geologic viewpoint, the site has no serious engineering problems. Indications are that blasting costs will not be excessive. Tunnel support will be required, but running ground is not anticipated in the tunnel section. Danger of landslides is minimized by the general dip of the beds into the slope. Groundwater may be a problem locally but no serious flooding problem is expected.

Since the geologic data presently available is inadequate for a report which is in any way complete, it is recommended that an exploration program designed to test the engineering properties of the rocks to be cut or tunnelled be undertaken before construction plans are finalized. It is further recommended that the areas selected for use as fill material be test drilled prior to final location of the borrow pits.
INTRODUCTION AND PURPOSE

This report covers the geology of an area of the foothills west of Stanford University campus which has been tentatively selected as the site for the proposed two-mile linear accelerator, referred to as Project "M". This report is part of a study of the general feasibility of the site and its threefold purpose is: (1) to study the geological suitability of this area for the project; (2) to aid the engineers in estimating the cost of excavations; and (3) to direct attention to special problems which may result from geologic conditions at the site.

LOCATION

The area investigated lies in Santa Clara and San Mateo counties and has the form of a northwest trending strip, one-half mile wide by three miles long. It is approximately bounded to the northeast by Junipero Serra Boulevard, to the west by Alpine Road, to the southwest by the crest of the easternmost range of hills, and to the east by Fremont Avenue.

PHYSIOGRAPHY

The area is on the northeastern slope of low foothills of the California Coast Ranges which border San Francisco Bay to the west. This range of hills in the mapped area reaches maximum elevations of about 500 feet along the ridge line bounding the area to the southwest. The terrain gradually descends northeasterly to the alluvial plain of the San Francisco Bay lowland at elevations of 150 to 200 feet.

Two streams flowing northeastward to San Francisco Bay provide the main drainage. San Francisquito Creek flows in a steep-walled valley near the western boundary of the area. Matadero Creek, with one important tributary meanders across an alluvial plain of low relief in the southeastern part of the area. Between these two main drainage-ways, intermittent streams have dissected the range into rounded hills.

Soil cover on the hilltops and slopes probably averages less than one foot. Soil and alluvium in the upper portions of the gullies probably average three or four feet, thickening downstream to about ten feet near the break in slope between the hills and the alluvial flat.

These hills are generally grass-covered with a few oak trees. Some of the steeper ravines are filled with brush.

REGIONAL CONSIDERATIONS

The proposed site of Project "M" lies in an area of faulted and folded late Mesozoic and Tertiary sediments and volcanic rocks. The recently active northwesterly trending San Andreas rift zone lies about three miles to the southwest of the site. The Hayward fault, another recently active fault zone, parallels the San Andreas approximately 20
miles to the northeast of the site. Numerous major and minor faults, with which no recent movement has been definitely linked, also occur in the area.

It is apparent that the proposed site is located in a region of tectonic instability. However, it is impossible to predict when severe earthquakes will occur and what effect they will have on the proposed structure. The tectonic instability of the entire Pacific Coast region should be carefully considered in the selection of a site for this project.

**SOURCES OF GEOLOGIC INFORMATION**

Probably less than one percent of the area is outcrop. These exposures, generally of the more resistant sandstones, limestones and volcanic rock, occur on top of ridges and in creek beds. Shales and soft sandstones, which are known to be present from excavations, rarely outcrop.

Rocks of the area are exposed in numerous road cuts and several basalt quarries. Several excavations no longer accessible have been described by previous writers.

Information from six holes drilled through the basalt in the southern part of the area was utilized in this report.

Several earlier reports and descriptive notes utilized in this work are listed in the bibliography. The map and several cross-sections prepared by Atchley and Grose (1954) are incorporated directly in this report.

**PRESENTATION OF DATA AND INTERPRETATIONS**

The map accompanying this report shows exposures of different rock types by black-and-white symbols. Distribution of various rock units as interpreted from these observations and from topography is shown by color. The lack of outcrops, complicated local structure and scarcity of continuous marker beds, make the interpretation of the geology highly speculative, especially in rocks older than the Los Trancos volcanics. The rock units mapped in the Searsville formation indicate only the general characteristics of the rocks and not the exact position of hard and soft sandstones and shales. The units selected for mapping in the Searsville formation are: (1) relatively hard rocks resistant to erosion: mostly hard, well consolidated sandstone but some soft sandstone and shale may be included; (2) rocks of medium hardness: dominantly medium hard sandstone, or interbeds of hard sandstone with soft sandstone and shale; and (3) relatively soft rocks with little resistance to erosion: soft sandstones and/or shales.
STRATIGRAPHY

General

The oldest beds exposed in the area mapped are sandstones and mudstones of Eocene (and Paleocene?) age. These are included in the Searsville formation by Thomas (1949). Overlying these beds with angular discordance are sandstones, volcanic rocks and sandy limestones assigned to the Miocene Los Trancos formation by Thomas. In topographically low areas, the Searsville formation and the Los Trancos formation are overlapped by unconsolidated gravels, sands and clays of the Plio-Pleistocene Santa Clara formation and by Recent alluvium. These youngest deposits have no direct bearing on Project "M" and therefore they have not been mapped or described.

Searsville Formation

The Searsville formation consists of interbedded sandstones, mudstones and shales. In that part of the area traversed by the linear accelerator the formation is about 3000 feet thick. It is estimated that the ratio of sandstone/mudstone is about 4:3. The sandstones are generally feldspathic, thick bedded to massive and medium to coarse grained with a kaolin matrix. They vary in their degree of consolidation from relatively loose, friable and weak to well-cemented with carbonate, hence extremely hard and strong. The argillaceous rocks are commonly yellowish buff, massive mudstone, but some grade to grayish and brownish fissile shales.

Thickness of the interlayers of sand and argillaceous rocks varies from several tens of feet to less than one foot. Although definite evidence is lacking, the difficulty of correlating bed for bed over short distances and the difficulty in tracing marker beds for any distance along strike indicates that lateral variations in lithology within the Searsville formation are common.

Los Trancos Formation

The Los Trancos formation can be conveniently divided into four members from the base upward. Member A: loose to poorly cemented sand; Member B: volcanic rock including basaltic flows and fragmental volcanic material; Member C: coarse fragmental sandy limestone; Member D: soft friable sandstone with rare mudstone layers.

Member A (TLA) overlies the Searsville formation with angular unconformity and underlies the Los Trancos volcanics. It is exposed only on Alpine Road and along San Francisquito Creek where its thickness is estimated at 75 to 100 feet. It consists dominantly of loose to well-cemented medium grained arkosic sand, but may include some coarse bioclastic limestone similar to Member C. It is not known to be present east of the valley of San Francisquito Creek.
Member B (T1B) consists dominantly of basaltic volcanic rocks which vary in thickness from about 65 feet on Alpine Road to a reported 600 feet along Page Mill Road (Atchley and Grose, 1954). In the western part of the area, the volcanic rock is dominantly aphanitic olivine basalt and vesicular basalt, very strong, hard, and dense where unweathered. In the basalt quarries along Page Mill Road, these flow rocks (T1BI) form only slightly more than half of the total thickness of volcanic rock. Irregularly interlayered with these flows are bands of fragmental volcanics (T1Bf) which have been variously described as tuff, breccia and agglomerate, but much of which appears to be conglomeratic. Possibly it was deposited as mud flows and landslides from the flanks of active volcanic cones and lava tongues. It consists dominantly of angular to subrounded fragments of volcanic rock, largely basalt, which range in size from less than one inch to several inches in diameter. Many of these fragments appear to have been weathered prior to induration of the rock mass. The fine matrix is not abundant, and although it may be largely altered ash and fine volcanic debris, some fine quartz and feldspathic sand is also present. This fragmental volcanic rock is structurally weak, and near the surface, at least, is badly weathered.

Member C (T1C) is probably less than 50 feet thick. It consists of well-cemented coarse shell fragments ("Barnacle Beds"), with interbedded hard calcareous sandstone. It is hard and relatively strong.

An unknown thickness of soft, buff, fine-grained arkosic sandstone with interbedded soft mudstones and shales directly overlying Member C exposed east of Page Mill Road is assigned to Member D of the Los Trancos formation (T1D). The sandstones of this member are indurated but poorly cemented and friable. Although assigned to the Miocene Los Trancos formation, it may be Pliocene in age.

**STRUCTURE**

Beds assigned to the Eocene Searsville formation generally strike northwest and dip 40 to 70 degrees to the southwest. The central core of Eocene rocks is bounded on three sides by the Miocene Los Trancos formation which dips away from it at about 10 degrees along the western boundary, and at 30 to 45 degrees along the southern and eastern boundaries.

Faulting complicates this semi-domal structure. A north-south trending fault with upthrown side to the east crosses Junipero Serra near the Matadero Creek bridge and results in the repetition of the Los Trancos volcanics (T1B) and overlying beds. A northwesterly trending fault having its upthrown side to the northeast passes between the two basalt quarries on Page Mill Road but apparently dies out before entering the area of Eocene rocks to the Northwest. A third fault is postulated passing between San Francisquito Creek and the old basalt quarry and trending northeasterly to the junction of Alturas Drive and Junipero Serra Boulevard. This last fault is based on these lines of
inconclusive evidence: (1) offset of bands of resistant beds as expressed by the topography; (2) discordant attitudes of beds of the Searsville formation near the trace of the postulated fault; (3) considerable difference in the general strike of the beds on opposite sides of the postulated fault; and (4) determination of a Paleocene or Early Eocene age for foraminiferal shales outcropping near the entrance to the Stanford Golf Course whereas foraminiferal shales outcropping on Junipero Serra Boulevard 1100 feet southeast of Alturas Drive have been determined as Late Eocene (E. Dean Milou, personal communication).

In addition to these three main faults, numerous smaller faults are doubtless present within the area. Where well exposed in excavations, mudstones and shales show evidence of much shearing and slippage, which however, may have resulted from downhill movement of the rocks or adjustments along bedding planes as a result of folding rather than movement along deep-seated faults.

ENGINEERING PROPERTIES OF THE ROCKS

Excavation

Rock breakage. - An attempt has been made on the map and sections to indicate the amount of blasting required for excavation. It should be emphasized that this is intended to serve as only a rough guide of hardness of the rock units relative to each other, and experience will indicate whether more or less blasting is required.

In construction of the Stanford Tunnel of the Hetch-Hetchy aqueduct, the mudstone and shales were mucked out with pneumatic spades and the sandstones were blasted (Lauenstein, 1951). Hence, it is felt that most or all of the mudstones and shales can be removed without blasting in both the open cut and tunnel. Probably many of the softer sandstones of the Searsville formation can also be removed with shovels, at least in the open cuts. Many of the hard sandstones of the Searsville formation will require blasting. Much of the poorly consolidated and fractured fragmental volcanic rock (TLBf) probably need not be blasted. The solid basalt flows (TLB1) will be mostly blasting rock, as will the overlying TIC. The soft sandstones and shales of T1D should be easily moved with a shovel.

Tunnel support. - During construction of the Stanford Tunnel of relatively small diameter (to accommodate 91 inch pipe), continuous installation of supports at four to five foot centers was required to combat swelling and flowage of the shales and mudstones of the Searsville formation. Similarly, the poorly consolidated fragmental volcanics (TLBf) and the fractured lavas (TLB1) will require at least some support during driving of the proposed tunnels.

Slopes of open-cuts. - Assuming adequate drainage, it is considered that permanent 1:1 slopes can be maintained in unweathered rock with the possible exception of the loose fragmental volcanic material. With the same exception, most of the other rocks will
probably stand up for a short period of time with a slope as steep as 4:1. The greatest difficulty in keeping cuts open with these side slopes is anticipated where shale beds dip toward rather than away from the excavation.

Landslides

Shearing and local contortions in mudstones and shales of the Searsville formation indicate that they flow easily. Landslides and slips on hillsides underlain by rocks similar to the Searsville formation is a serious problem where the beds dip in the direction of the slope. Fortunately, in the area of the proposed site, the Searsville formation has a dominant southwest dip whereas the slopes are mainly northeasterly. Good drainage is recommended to minimize the danger of slippage along argillaceous strata.

The soil derived from the Searsville formation is clayey and probably highly plastic when wet. It is recommended that this material be stripped prior to placing fill, and that it not be utilized as fill material.

Groundwater

The writers are not aware of good aquifers within the Searsville formation, although some of the hard sandstones, if fractured, may bear large quantities of water. The jointed basalts and fractured fragmental volcanic rocks are known to be excellent aquifers in the area and will probably be locally water-bearing where encountered only by the proposed line of the accelerator. In the Hetch-Hetchy excavations, water control measures were required in hard sandstones overlying the volcanic rocks, but these beds will probably not be encountered in excavations for the accelerator.

Fill Material

The large volume of fill needed near the southeast end of the accelerator can probably be obtained from the elongated hill about one-half mile due south of the intersection of Page Mill Road and Junipero Serra Boulevard. Although outcrops are lacking, the hill is believed to be composed of soft sandstone and shale of TID. It should be test-drilled before definite plans are made to use it for fill material.

The location of adequate fill material for the western portion of the project requires further study.

Conclusions

Regarding the geologic suitability of the site, it is concluded that:

1. The site is located in the tectonically unstable Pacific Coast region and is about three miles from the recently active San
Andreas fault zone. The location of the project parallel rather than at a high angle to the trend of the San Andreas zone probably reduces the chance of offsetting the line of the accelerator during a major earthquake.

2. Several faults cut through the area of the proposed site. There is no evidence of recent movement along them.

3. There is no indication that costs of excavation of rock cuts and tunnels will be excessively high. Rock breakage costs should be comparatively low. Tunnel support will doubtless be required but there are no indications of extremely loose, running ground. Side slopes of cuts should stand up well.

4. Landslide danger along the argillaceous beds is minimized by the general dip of the Searsville beds into the slope.

5. Groundwater may be a problem locally but no serious flooding of workings is expected.

This paper is to be regarded as a preliminary report since the available geologic information is far from adequate for a complete study of the site. Before construction plans are finalized, a drilling program should be undertaken to explore the portions of the line which are to be cut or tunnelled and engineering tests made on the materials which will be encountered.


Page, B. M., 1947, Geology along the P. G. and E. pipeline, Page Mill Road and Junipero Serra Boulevard: unpublished notes.

Silberling, N. J., and Waldron, J. F., 1951, The geology along the Bay Division Pipeline No. 3: unpublished manuscript, prepared for the California Division of Mines.

Thomas, R. G., 1949, Geology of the northwest part of the Palo Alto quadrangle, California: unpublished map, Stanford School of Mineral Sciences.
July 20, 1959

Mr. F. V. L. Pindar
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

Dear Sir:

For several years we have been developing certain information in connection with the proposed construction of the Linear Accelerator. During this period, through discussions and correspondence, we have presented our recommendations on the design and construction of the complete facility. These recommendations, in turn, were based on extensive studies and analyses accomplished by our company, as well as information available on the proposed site prepared by others.

While we understand that construction work on the project will be preceded by the normal exploration, geological and related surveys, it is our opinion that the general proposed area will be feasible for construction and presents no abnormal problems in relation to earthquake hazards.

In that connection we have attached a report prepared by Mr. Clark E. McHuron, our Consulting Engineering Geologist, who has studied this problem and further expresses our views in this matter.

We appreciate the opportunity to present this information.

Very truly yours,

C. S. Davis
General Vice President

GSD:mf
Attach.
July 20, 1959

Utah Construction Company
One Hundred Bush Street
San Francisco 4, California

Attention: Mr. C. S. Davis, General Vice President

Subject: Stanford Two-Mile Linear Accelerator

Dear Mr. Davis:

After carefully reviewing the diamond drill core data of the Utah Construction Company together with the accompanying geologic data for the proposed site area for the Stanford Accelerator immediately South of Stanford University, walking out the entire area on two different occasions, as well as subsequently making an aerial site inspection and stereoscopic examination of the aerial photographs, the writer makes the following statement:

It is understood that a suitable subsurface investigation study will be made. Providing the above is satisfactorily completed, it is the considered opinion of the writer that final tunnel alignments can be located within the general proposed area which are entirely feasible for construction and which appear in all reasonable probability to be within design and operational tolerances as regards possible earth movements.

Respectfully submitted,

[Signature]

Clark E. McHuron

In duplicate

[Stamp]
July 17, 1959

Dr. Edward Ginzton
Microwave Laboratory
Stanford University
Palo Alto, California

Dear Dr. Ginzton:

Enclosed is the report of our Chief Consulting Geologist - Roger Rhoades - concerning the site geology for the proposed Stanford Linear Accelerator.

Mr. Rhoades is a consultant for major hydro-electric and hydraulic studies and engineering with Bechtel Corporation as well as other clients in the United States, Australia, Pakistan, Canada and the South American countries. Before entering private practice, Mr. Rhoades was a geologist for the Tennessee Valley Authority and Chief Geologist for the Bureau of Reclamation.

In transmitting Mr. Rhoades' report, I should like to point out that the Hetch Hetchy Aqueduct, supplying water to San Francisco and other communities in the Bay Area, was recently constructed very close to and generally parallel to the site of the proposed accelerator.

If there are any other questions or problems with which we may be of service, please call on us.

Sincerely,

[Signature]

Wade Dickinson

WD/vs
Enclosure
Mr. B. W. O. Dickinson
Bechtel Corporation
225 Bush Street
San Francisco, California

Dear Mr. Dickinson:

I have again reviewed the available geologic data, maps, cross sections, and report relevant to the seismic potential of the area in which it is proposed to erect the Stanford accelerator.

A tunnel or equivalent cut-and-cover system some two miles in length is proposed. This line is crossed by two faults and possibly by a third. There may also be other zones of shear or fault-like displacements of smaller magnitude which cannot be discerned on the ground surface. These are all old faults without any evidence of movement in the historic times. I consider them to be inactive faults, and that the chances of their resuming activity are negligible. For this reason, I can foresee no danger that the structure would be physically broken or offset, or its alignment distorted.

The San Andreas fault zone lies a few miles to the west. Stanford University has experienced earthquake vibrations emanating from this fault zone, notably in 1906. The accelerator installation in question would probably experience similar effects from time to time but probably not frequently.

I wish to make it clear that I am talking of two different things. First, the faults which actually cross the line of the proposed tunnel or cut-and-cover structure are old and inactive, and would not, in my opinion, jeopardize the structure. Second, a known active fault lies a few miles to the west of this area, and from it there will emanate earthquake effects in the future as in the past.

Naturally, the design and construction of the structure would incorporate the usual features for earthquake resistance; but this is standard engineering practice in regions where earthquakes are expectable.

Sincerely yours,

[Signature]

Roger Rhoades
Consulting Geologist

RR:dk
July 16, 1959

Dr. F. V. L. Pindar
Associate Director
Hansen Laboratories of Physics
Stanford University
Palo Alto, California

Dear Dr. Pindar:

In reply to your inquiry with respect to the feasibility of tunneling in the proposed location for the Stanford Linear Accelerator, the following is the comment of our geologist, Mr. D. J. Frost.

Based upon a field reconnaissance of the proposed site and adjacent area, it is his opinion that:

1. The proposed tunnels will pass through and be constructed in rocks which will afford better general tunnel driving conditions than are average for the general Central Coast Range area of California.

2. The two minor fault fracture areas which cross the tunnel site are thrust type, are of probable Pleistocene age, and are now inactive. Since they are unrelated to the San Andreas System complex, no significant movement is expected along these fracture zones.

3. Referring general catastrophic wide spread West Coast earth movements, the long range physical stability of the constructed tunnels would be expected.

These opinions are based on an inspection of the surface, and on general knowledge and experience in this area. We recommend, of course, that a program of investigation of the proposed site by core drilling be undertaken.

Very truly yours,

KAISER ENGINEERS
Division of Henry J. Kaiser Company

David F. Shaw
Vice President

DFS:hs
APPENDIX F

SELECTED REFERENCES

The following references were extensively consulted during the preparation of this report. Many other sources have been examined, and a complete bibliography is being compiled. However, publications listed are those which are most pertinent to the present investigation.


6. Jenkins, O. P. Geologic Guidebook of the San Francisco Bay Counties. Bull. 154, California Division of Mines (1951). (Contains a review of regional geology and an article by Dr. Byerly on the earthquake history of the area.)


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18. - - - - - - Santa Clara Valley Investigation. Bull. 7, California State Water Resources Board (1955).