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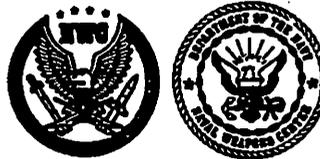
OFFICE

Engineering and Environmental Geology of the Indian Wells Valley Area

by
John T. Zellmer
Research Department

NOVEMBER 1987

**NAVAL WEAPONS CENTER
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ABSTRACT

The IWV area of southeastern California, is affected by several geologic and geotechnical hazards and problems. These include seismic activity, a limited ground-water resource, flooding, poor soil conditions, slope instability, liquefaction susceptibility, a locally high ground-water table, sewage and toxic waste disposal, and the potential for volcanic activity. Many of the present difficulties are directly or indirectly related to the rapid wartime building of the Naval Ordnance Test Station (now Naval Weapons Center), China Lake, during which adequate consideration was not always given to the geologic and geotechnical factors that affect the local area and region. Now that various problems and hazards have been recognized, efforts are under way to mitigate the deleterious effects of past actions and decisions and to prevent their recurrence. A major factor in these efforts is the increasing involvement of geologic and geotechnical data and expertise in decision making.

INTRODUCTION

Indian Wells Valley (IWV) is located in southeastern California within the southwestern corner of the Great Basin and is bordered by the Sierra Nevada Range to the west and the Mojave Desert to the south. Tectonic and volcanic activity during the last 2 to 3 Ma shaped much of the present physiographic and geologic character of the region and continue to exert a combined influence. The interaction of physiography, geology, and climate of the area confront the local populace with a variety of geologic hazards and interrelated engineering and environmental geology problems. These can be grouped under the general categories of active faulting and earthquakes, potential for volcanic activity, ground water, flooding, slope instability, sewage and toxic waste disposal, and poor soil conditions. These problems and geologic hazards are not atypical of those encountered elsewhere in the desert southwest.

Many of today's engineering geology problems result from the rapid, wartime building of the Naval Ordnance Test Station, now the Naval Weapons Center (NWC) at China Lake. Prior to 1943, the population of IWV numbered about 300 and lived for the most part on small ranches and farms. The current population is about 30,000, most of whom live in the City of Ridgecrest. With the advent of NWC the population exploded, and because of wartime urgency, development occurred at furious pace and often without adequate consideration of the geologic environment and the future. As a result, many structures and facilities were constructed at convenient but geologically

communications systems; more extensive geotechnical investigations of proposed building sites; development and implementation of emergency action plans; developing closer ties between the U.S.G.S., NWC staff geologists, and NWC management; at-home storing of food and water; attaching bookcases, etc., to walls; and learning to shut off gas lines and electrical circuits. For the last several years local geologists and disaster preparedness personnel have been in demand by civic service organizations and other groups to make presentations and answer questions that deal with various aspects of the local and regional earthquake hazards.

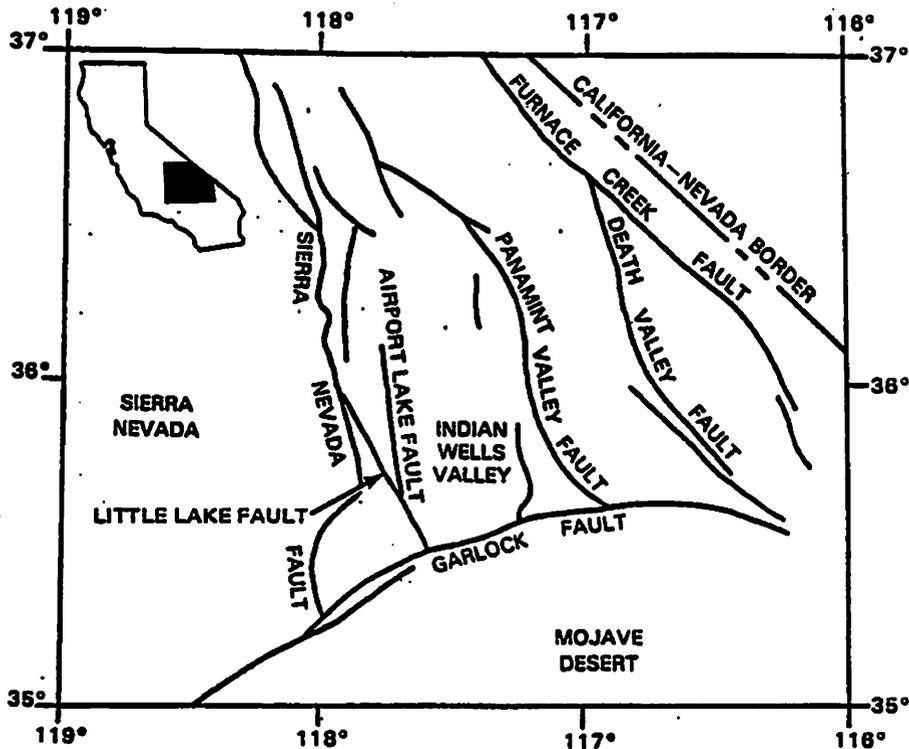


FIGURE 1. Active Faults of the Indian Wells Valley Region.

Paleoseismicity studies have shown that the LLFZ and ALFZ are probably capable of producing earthquakes in the $M=6.4$ to $M=7.4$ range with estimated recurrence intervals of 784 to 4000 years, respectively (Reference 7). Larger earthquakes, perhaps in excess of $M=8.0$, may be possible if interaction between the Sierra Nevada fault and LLFZ occurs. This is especially likely in that the LLFZ is an active splay of the Sierra Nevada fault that appears to be accommodating the right slip that occurs along the Sierra Nevada fault north of the faults' intersection. Earthquakes of these magnitudes should be considered as

maximum credible earthquakes. Although maximum probable earthquakes have not yet been determined, $M=6$ seems reasonable and is the value used in the above mentioned U.S.G.S. notification. Using only the historic record, we find that magnitude 5 could be considered as a "characteristic" earthquake (Reference 8) for the LLFZ, as three earthquakes of $M=4.8$ to $M=5.1$ have occurred along the fault since 1938. Recurrence intervals have been 23 and 21 years. The most recent, in 1982, marked the culmination of nearly 2 years of seismic swarm activity in which larger numbers of earthquakes with progressively larger principal magnitudes occurred with successive swarms.

Several seismic swarms with principal magnitudes of $M=4.0$ to $M=4.7$ have also occurred along the ALFZ. Seismic studies by Walck and Clayton suggest, however, that these swarms are related to volcanic activity (Reference 9). Zellmer, Sanders, and Roquemore agree with this conclusion, but they also point out the probability of synergism between volcanic and tectonic activity in the area (Reference 10). Sanders and others have shown that the swarm activity was probably related to magma migration within 3 km of the surface (Reference 11). Volcanic activity is addressed in greater detail in a later section.

Mapping of active faults has shown that the LLFZ and ALFZ extend beneath several important NWC facilities and through Ridgecrest (Figure 2 and Reference 2). Epicentral maps suggest that the LLFZ and ALFZ may be related to a deeper and highly active fault zone that lacks surface expression but strikes NW-SE across IWV, parallel to but slightly offset to the east from the LLFZ and terminates against the Garlock fault (Reference 4 and unpublished U.S.G.S. data). Recent work by Bent and others, however, indicates that the offset is the result of the eastward dip of the LLFZ, which places epicenters east of the mapped fault traces (Reference 12). Figure 3 shows the epicenters for the approximately 3000 earthquakes that occurred in the IWV area during 1986. The trends are nearly identical to those shown on plots of seismicity for previous years. According to Norris and others, this area was one of the most seismically active regions of California during 1986 (Reference 4).

Although the 1981-82 seismic activity occurred on the NWC test ranges, the southward continuations of the faults (Figure 4) indicate that future activity may occur within Ridgecrest. This is supported by the southward migration of epicenters during the 1981-82 earthquake swarms. About 10 km north of Ridgecrest the LLFZ and ALFZ combine to form a left-stepping, en echelon fault zone. The zone becomes indistinct in the Ridgecrest area because of its subtle surface expression and the superimposed cultural disruption that has occurred during the last half century. As a result, Roquemore and Zellmer have recommended the establishment of a seismic-hazard special studies zone (SSZ) that includes known fault traces and a buffer zone within the City of Ridgecrest (Reference 2). All new construction within this

data obtained from the monitoring systems is continually evaluated. Data and interpretations resulting from these studies are available to individuals, planners, and other interested parties.

VOLCANIC ACTIVITY

Volcanic activity has played a major role in the development of the northern portion of the IWV and the formation of the Coso Range (References 27 and 28). Recent data suggest that the local volcanism that has been occurring for at least the last 3 Ma has extended southward into the valley. Analysis of seismic and other data has led to the conclusion that at least two and possibly more areas of the valley are underlain by molten rock (References 9 through 11 and 29).

The seismic technique first used to locate and characterize the magmatic bodies is the same as that previously used to investigate intrusive activity at the Mammoth Lakes area, about 200 km to the north (Reference 30). The technique involves an analysis of P and S wave arrival times and waveforms. Studies have shown that P waves passing through molten rock are of smaller amplitudes and arrive later than rays not passing through the body. S waves that pass through molten rock generally arrive late, are markedly attenuated, and occasionally are absent from the waveform. These are also the characteristics of seismic waves passing through portions of the IWV. Other data, such as thermal ground-water wells that also emanate a hydrogen sulfide odor, and localized ground deformation support the conclusion of shallow magma bodies (Reference 10).

The possibility of shallow magma bodies existing beneath the IWV has stimulated a large amount of scientific interest. Consequently, a low-level research effort is being conducted by NWC in association with members of three other institutions. This research is focusing on seismic wave studies to better locate and characterize the probable magma bodies. Existing U.S.G.S. seismic stations and portable seismic event recorders are currently being used to collect data. These data are analyzed using tomographic inversion of compressional waves to obtain a three-dimensional seismic velocity structure of the region encompassing the postulated magma bodies (Reference 9). The resulting velocity structures indicate that the magma bodies are shallow sill-like forms with tops at a depth of about 3 km and bases about 5 km. More recent seismic data analyses by Sanders and others suggest that the bodies are tabular or plume shaped and appear to be fed at their bases by a narrow dike or pipe, possibly coincident with the Sierra Nevada fault (Reference 11). As yet there are no data to indicate that the bodies are increasing in volume or pose a threat of eruption within the foreseeable future. These data suggest, however, that the

transport velocities, and thicknesses of various eruption products (References 37 through 40). Figure 5 shows the expected thickness of the pyroclastic flow and surge deposits and the velocity at which they would be transported at various locations relative to the eruption center. The model superimposes a Mt. St. Helens-size eruption on the topography of the Coso volcanic area and IWV. These data are being used to determine the hazard that may result from future volcanic activity in the IWV. The computer model can also be easily tailored to other volcanic areas and has attracted international attention, largely because of its potential use in educating government officials and the general public of the potential hazards associated with volcanic eruptions.

FLASH FLOODING AND DEBRIS FLOWS

The IWV lies near the northern border of the Mojave Desert. The elevation of the valley floor is at about 725 m, and the surrounding mountains rise to elevations in excess of 2500 m. Annual precipitation averages 9 cm on the valley floor and about 25 cm in the surrounding mountains, most of which occurs during the winter; but late summer thunderstorms are common and often destructive. During 1983 and 1984, rainfall from thunderstorms in nearby mountain areas resulted in severe flash flooding within Ridgecrest and at NWC. Flood damage during the 1984 storm totalled \$40,000,000, about 75% of which occurred to NWC facilities. Although no deaths were attributed to the 1984 flood, several persons were saved from drowning or serious injury. During the 1983 flooding, one person died when her car was swept from the highway and another narrowly avoided the same fate when her car was swept nearly 2 km downstream by a flash flood. Debris floods and debris flows that occurred at the same time and discussed here without differentiation, destroyed, damaged or buried roads and structures. Up to 2 m of sand was deposited against the outside of some NWC buildings and a meter or more of sediment was not uncommon within certain buildings, after the flood waters battered open heavy steel doors. The basement and first floor of the largest laboratory complex at NWC were flooded by 3 m of water and mud that caused nearly \$30,000,000 of damage, destroyed thousands of irreplaceable documents that were in storage, and disrupted research for several months. Sheet flooding with estimated depths of 50 cm inundated many areas.

The major population areas and most of the NWC facilities are located between the China Lake playa and the southern end of the IWV (Figure 2). Much of the local drainage issuing from the Sierra Nevada, El Paso Mountains, Rademacher Hills, and Spangler Hills flows in a north to northeast direction through developed and semideveloped areas to the local base level at China Lake playa. Except where diverted by roads, residential and commercial development or artificial channels, the flood waters are generally confined to well defined arroyos. Flood water diversions and impoundments resulting from human intervention are largely responsible for the flood damage. City streets have become unplanned flood channels of sufficient magnitude to sweep automobiles downstream. Poorly designed and maintained culverts and artificial drainage channels resulted in water impoundments and unplanned diversions. The problem is continually exacerbated by vegetation removal and building construction that decreases infiltration and increases runoff and runoff velocity. Because of the large amount of development that is occurring and being planned in the Ridgecrest area, the problem is likely to increase in severity, unless mitigative steps are taken, several of which are being considered.

As was stated earlier, most of the damage to the populated areas of NWC resulted from drainages that were inadequate to accommodate the runoff from the 1984, 60-year storm. Consequently, the important drainage channels are being improved. Depending on local conditions, this has involved cleaning, widening, deepening, increasing embankment height; building diversion embankments; installing markedly larger culverts; and installing a low, concrete diversion wall around the major laboratory complex that was substantially damaged during the 1984 flood. Many of the undersized culverts and drainage channels that resulted in flooding of the laboratory have been improved; and a new, high volume drainage channel that leads directly to the playa has been excavated. In other areas, berms now protect facilities that were previously damaged. Emergency plans have also been prepared for mobilizing men, equipment, and materials to quickly erect temporary berms, widen channels, and complete other projects whose need may develop during a flood or flood warning. The NWC weather office will also issue warnings whenever conditions conducive to heavy rainfall are anticipated so that appropriate preparatory actions can be taken. These mitigation projects, when integrated with future construction, should divert and restrict most of the flood water to adequately sized drainage channels. The water can then be safely transported away from the major work areas and instead be allowed to flood the China Lake playa, the local base level. Flash flood warnings will allow for the mobilization of men, equipment, and materials to better protect critical facilities and areas.

The City of Ridgecrest has been less effective than NWC in its efforts to reduce future flood damage, but is moving forward. Flood damage repair and mitigation are only two of the major problems facing the rapidly growing city, and the lack of action is largely related to budgetary constraints rather than lack of concern. The City is currently completing a major redevelopment plan that should address many of the flood-related problems. In concert with this action, the U.S. Army Corps of Engineers is being asked to assess the flooding problem and develop mitigation plans that will probably involve the interception and diversion of flood waters away from developed areas and areas zoned for development.

GROUND WATER

Within the next several years IWV, as has happened to many other desert communities, will begin to experience the effects of groundwater overdraft unless extensive water conservation steps are implemented or other sources of water are developed (Reference 41). Studies by the U.S.G.S. have shown that pumpage has exceeded mean long-term annual recharge since 1966 (Reference 42). Located in a

The progressively declining water table levels in many areas argue for ground-water mining. Continued lowering of the water table will severely aggravate the existing water problem through contamination of the potable water aquifers by an influx of highly saline ground water that is now largely restricted to the China Lake playa. St. Amand's analysis indicates that the overdraft will eventually cause a reversal in the ground-water flow gradients that will allow migration of saline waters from the near-surface aquifer near the playa into the surrounding and underlying potable aquifer (Reference 41). Predictions based on mathematical ground-water modeling by Mallory indicate that the direction of flow could locally have reversed as early as 1984 and that a pronounced reversed gradient would be established by 2020 (Reference 47). Also, overpumping may affect the state of stress at depth and allow underlying saline waters to migrate vertically into the limited overlying potable aquifers (Reference 41). Contamination by an influx of saline water has forced the abandonment of one of the major domestic water pump fields. Most of the ground-water availability problem can be overcome by reducing the excessive demand now placed on a limited resource by conservation, reuse, and improved withdrawal schemes.

The intrusion of saline water is only one of the many contaminants that may adversely affect the local ground water. Prior to the recognition of the environmental consequences that are so well known today, disposal of toxic wastes by surface dumping, shallow burial or injection occurred at several NWC locations and possibly in the surrounding communities and undeveloped desert areas. A number of former disposal sites at NWC have been identified and are being studied or decontaminated (Reference 43, 48, and 49). These sites contain a range of toxic materials including aviation fuels, solvents, beryllium, propellants, explosives, pyrotechnics, laboratory waste, heavy metals, cyanide, industrial detergents, degreasers, and other materials. The decontamination effort has only begun and several years will be required to complete the task.

Major factors affecting the decontamination effort include identifying the sites because of the loss or lack of records; determining the toxic materials that are or may be present; determining the mobility of the contaminants and potential dispersal methods; determining the potential hazard; and designing and implementing decontamination procedures when necessary. Several studies have been undertaken to answer these questions, and as a result, decontamination of some sites has begun and others are scheduled in the near future.

Aviation fuels, solvents, and fluids present one of the largest problems in terms of disposed volume and affected area. Between 1945 and 1982, an estimated 3.8×10^6 liters of substandard aviation and jet fuel was disposed of at Armitage Field (Figure 2) in dry wells or

Several problems have complicated implementing a solution to the ground-water problem. These include the coordination of several jurisdictions and attaining agreement commensurate with the responsibilities of each, agreeing on a solution or range of solutions, obtaining funding and accommodating the Mojave tui chub (*Gila bicolor mojavensis*), a Federally-protected fish. The sewage treatment plant and ponds were expanded and upgraded during the mid 1970's to combine the waste disposal systems of NWC and the City of Ridgecrest into a single facility (Figure 6). The facility is located on NWC at the site of the original NWC sewage ponds that is operated by the City with NWC considered as a customer. The permits under which the new ponds were constructed stipulated that they would be for evaporation only. Because they are in violation of the original operating permits and are contaminating the ground water, the State Water Quality Control Board is in the process of ordering the City to bring the ponds into compliance.

The City, in conjunction with an environmental engineering consulting firm, has determined that repairing or replacing the ponds is not economically feasible. Alternatively, it appears that exporting partially treated water to adjacent Searles Valley for industrial usage is practical from both economic and engineering considerations. Exportation of the water is attractive in that it would mitigate the infiltration and consequent ground-water flooding problem, it could generate revenue to offset construction and operating costs of the pipeline, and industrial use of the water would decrease the demand for potable ground water from IWW. The City's consultant estimates that about $3.1 \times 10^6 \text{ m}^3$ of industrial use water is available for export and that this volume may double by the year 2010. Exportation of the water will require the construction of a 41 cm diameter pipe line 35 km long, pumping facilities and possibly a well point dewatering system down-gradient from the sewage ponds. If the exportation plan is approved the water table will gradually decrease to the pre-mid 1970s elevations, resulting in diminishing damage and operational handicaps for NWC.

A general lowering of the water table will however, create other problems unless provisions are made to maintain the water level within the Mojave tui chub habitat. In 1971, the California Department of Fish and Game planted a small population of the endangered fish into a pond and marsh area locally known as Lark Seep and located north and down-gradient of the sewer ponds (Figure 6). It is now known that the habitat, originally thought naturally spring fed, is actually maintained by leakage from original NWC sewage ponds built during the early 1940s and by the newer City ponds.

The chub found the Lark Seep area and its drainage channels to be an ideal habitat that allowed it to thrive while other populations rapidly disappeared, and NWC now has one of the few if not the only

liquefaction susceptibilities (Reference 50). Recent geotechnical and geologic investigations have verified Banks' mapping in many areas. Any local earthquakes significantly larger than the 1982 event will probably have serious consequences for NWC, especially where the water table has risen.

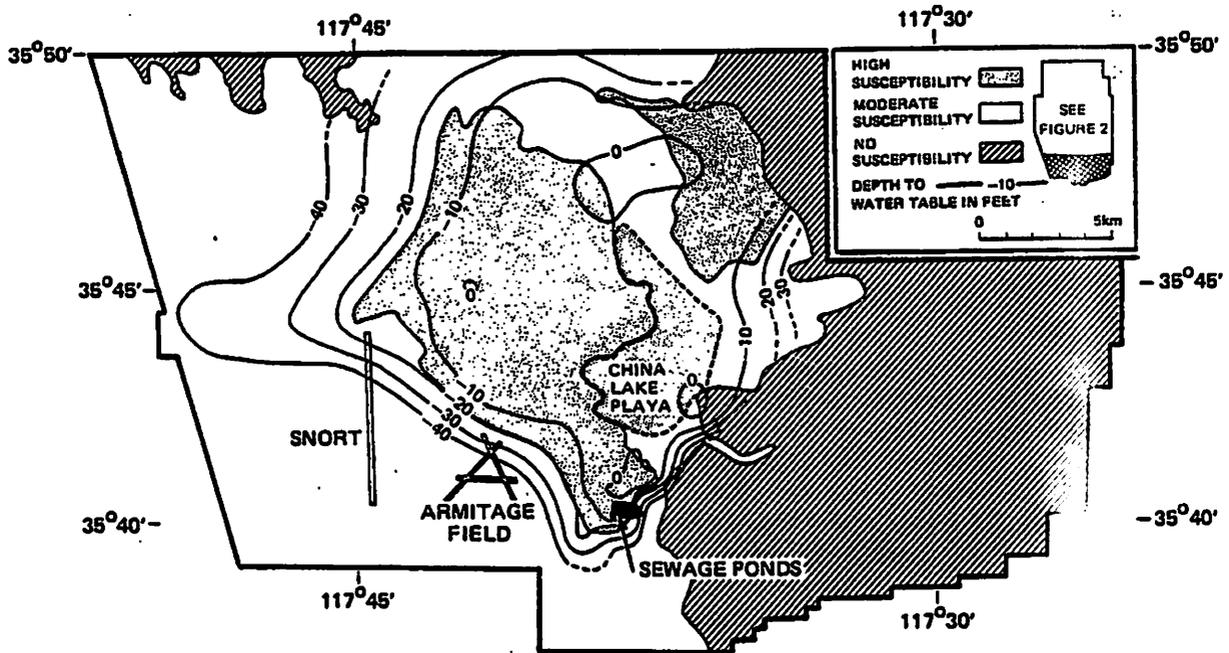


FIGURE 7. Map Showing Liquefaction Susceptibility of the Southern Portion of the NWC Test Range Area. (Modified from Reference 50.)

Ridgecrest and other populated areas of the valley would be less affected by liquefaction because of the deeper water table and tendency for coarser sediments to occur away from the playa area. There are, however, several areas that may be susceptible to liquefaction-induced slope failures, such as lateral spreading. Gentle slopes underlain by liquefaction-susceptible sediments occur within limited areas of NWC, especially north and northeast of China Lake playa (Figure 2). This unpopulated and largely undeveloped area contains southwest-dipping slopes with angles of 1 to 2 degrees. Slopes with angles as gentle as 0.3 degree have failed by lateral spreading (References 51 and 52). Slopes exceeding 0.3 degree are common throughout much of the area studied by Banks and their materials were found to be highly or moderately susceptible to liquefaction (Reference 50). Liquefaction-induced lateral spreading and associated soil failure could conceivably occur over many areas of NWC where water table is less than 10 m deep (Figure 7), but the sparsity of development in these areas would generally limit the damage to roads and utility corridors.

SLOPE FAILURE

Slope failure hazards in the IWV area are generally limited to rock falls and landsliding from the steep slopes and canyon walls of the surrounding mountains that would most likely be triggered by earthquakes. However, development in and adjacent to mountainous areas aggravates the limited hazard that now exists from occasional rockfalls and landslides unrelated to seismic shaking. During an airphoto reconnaissance of the region, six landslides exceeding 0.5 km² in area were recognized. These include three in the Coso Range granitic rocks with areas of 0.6, 1.4, and 2.1 km²; one in Coso Range volcanic rocks of 1.9 km²; one in the central Argus Range volcanic rocks of 6.7 km²; and one in Sierra Nevada granitic rocks of 10.0 km². Although none of these have been studied in detail, they appear to be late Pleistocene to early or mid Holocene in age. The scarcity of young landslides of this size probably results from the present arid climate that has dominated the region during much of the Holocene.

Although the arid climate and thin, poorly developed soils in many areas will diminish the number of slope failures, rock falls and rock slides are likely to occur. Well-developed jointing with orientations favorable to slope failure commonly occurs in the steep mountain areas. Because these areas are largely unpopulated, the greatest impact will be to transportation routes. Even minor slope failures could prevent access to many areas. At NWC the greatest hazard exists in Mountain Springs Canyon (Figure 2). Here, an access road extends about 8 km through a 500-m-deep canyon with slopes averaging 35 degrees, but locally are considerably steeper. Well-developed orthogonal joints that yield granitic blocks of several cubic meters in volume intersect the canyon walls. In some highly sheared or weathered bedrock supports the road and topographic slopes. In other areas the road passes through colluvium and alluvial fan deposits with cut slopes of 3/4:1 to 1/2:1 (horizontal to vertical) and heights up to about 17 m. In areas of limited slope stability, catchments were constructed, where space permitted, to catch falling rock; and large, potentially unstable, boulders were removed by blasting. The slope problem is aggravated by undercutting of the ephemeral stream that drains the canyon. Flash flooding of the stream seriously damaged the road in 1984. Although the road through the canyon has been rebuilt, cost factors prevented complete removal of the rockfall and slope stability hazard, especially where it could be required by seismic considerations.

Historically, road closures due to slope failure have not been a problem in the area, but the potential for seismic shaking under this fortuitous circumstance. As was discussed previously, the area lies within a highly seismically active region. References are given in a

CONCLUSIONS

Most of the geologic hazards and geotechnical problems that affect the IWV area are related directly or indirectly to the site selection and development that proceeded without the least adequate consideration for the environment and the local geology that is now considered necessary. Numerous steps are now being taken to minimize the deleterious effects of the earlier actions and to prevent their repetition. As a result of experience and modern geologic and geotechnical investigations, site selection and design now incorporate a much higher level of geologic and geotechnical detail than was previously included. Reconnaissance and detailed studies of the local geology and geotechnical parameters will continue, now that their importance has been recognized. Although development will still occur in geotechnically unfavorable areas, structures are more adequately designed to accommodate site conditions that previously may have gone unrecognized or not have been fully appreciated.

In the long term, the most serious problems to affect the area will be an adequate water supply and the effects of seismicity. Even though the longevity of the ground-water supply is generally known to be in question, there is still a demand for increased development, highly water-consumptive agricultural usage, humid-landscaping, and additional recreational amenities such as golf courses, swimming pools, and "water parks." Although many of these are desirable, considerations of the implications of increased demand and the limited water supply are sometimes subordinated to economic arguments and personal wants. In the populated desert south-west, the seriousness of a limited water resource is often not fully appreciated by our modern society at large until water rates rise substantially or until nothing happens when the spigot is opened. It appears that this problem can be solved only by education of the public and the actions of enlightened and farsighted public officials.

The mitigation of earthquake hazards must be through public awareness, that is, through public awareness and governmental zoning and site investigation requirements. Moderate to major earthquakes are inevitable in this region and their effects must be addressed. Recognizing this necessity, NWC provided funding for mapping of active faults, seismicity studies, liquefaction potential studies, and for obtaining other critical geologic and geotechnical information. These data, in combination with public awareness, have resulted in major advances in seismic hazard mitigation efforts in the private and public sectors.

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