Improving Seismic Safety of Dams in California

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Abstract

A search of the dam files at California's Division of Safety of Dams has revealed that at least 94 dams have been improved for seismic stability. The results of the search are tabulated and discussed. Improvements to seven of the dams are reviewed to illustrate the range of methods used and to note important factors. Design considerations in addition to liquefaction, stability, and settlement analyses are discussed. Reservoir restrictions and emergency responses are briefly covered.

Introduction

On March 12, 1928, the sudden failure of St. Francis Dam in Southern California resulted in a major disaster. Because of this failure and because of the potential risk to the general populace from a growing number of water storage dams in California, the Legislature in 1929 enacted statutes providing for the supervision over non-federal dams by the State. Before the enactment of these statutes, State supervision was limited in scope and covered only about half the dams in the State. The new laws provided for (1) examination and approval or repair of dams completed prior to the effective date of the statute, (2) approval of plans and specifications for and supervision of the construction or modification of dams and (3) supervision of operation and maintenance of dams. More than 1200 dams are currently under the supervision of the Department of Water Resources' Division of Safety of Dams.

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The San Andreas fault traverses three quarters of the State's 800 mile length, passing through its largest population centers. Numerous lesser known active and potentially active faults are dispersed throughout most of the State. Seismic stability of dams has been a concern of State engineers since as early as the 1920s. The focus at that time was on multiple arch dams. Those structures, while making very efficient use of the lightly reinforced concrete to support reservoir loads, have little resistance to cross channel motions that can be caused by earthquakes. The State was successful in using the new law to compel the owner of Lake Hodges Dam, a multiple arch structure in San Diego County, to correct this deficiency in 1936. The effort was no doubt aided by the devastating 1933 Long Beach Earthquake which killed 120 people, primarily in building failures.

Two hydraulic fill dams were damaged by the 1952 Kern County Earthquake -- Dry Canyon Dam 45 miles from the epicenter and South Haiwee 95 miles from the epicenter (Seed et al, 1978). The owner of the dams recognizing they were in areas of high seismicity, hence subject to more severe shaking, acted to stabilize the dams. A 120-foot wide rockfill berm was added to the upstream slope and a 100-foot wide berm to the downstream slope of 81-foot high South Haiwee Dam. A massive earthfill downstream buttress, 13 feet higher than the existing 66-foot high embankment, was constructed at Dry Canyon Dam.

The near disastrous performance of Lower San Fernando and the displacement of Upper San Fernando, near Los Angeles, during and immediately following the February 9, 1971 earthquake, confirmed concerns that hydraulic fill dams could be severely damaged by earthquake induced vibrations. Public interest in dam safety was renewed by the incident. Reacting to this situation, DSOD ordered the owners of the 36 known hydraulic fill dams to have their dams analyzed using the state-of-the-art Seed-Lee-Idriss dynamic analysis procedure (Jansen et al 1976). Most of the improvements discussed below are the result of those orders, initiatives of dam owners, and subsequent orders to owners of non-hydraulic fill embankments and concrete dams.

Improvement of Dams

The dam files at DSOD were researched using a very broad definition of improvement of dams for seismic stability. Ninety four improved dams were identified.

The improvements ranged from removing dams, to performing structural repairs, to restricting reservoir storage. Table 1 summarizes the improvements.

As might be expected, replacing dams, adding buttresses and berms, flattening slopes and draining and grouting foundations have been frequent improvements. Their expense has driven the other major class of improvements: lowering spillways, taking dams out of service and restricting reservoir storage. The reduced costs represent a trade off in reservoir value to the owners. Other safety deficiencies such as inadequate spillway capacities have also led to lowering spillways or taking dams out of service. The replacement of a reservoir by the tanks option has sometimes been selected to meet increased water quality standards as well as abating dam safety concerns.

Table 1-Improvements to Dams

Berms added or slopes flattened on embankments	19
Freeboard increased by adding embankment	3
Freeboard increased by lowering spillway, removing spillway gates, etc	15
Crack stopper zones added	6
Concrete dams buttressed with concrete	4
Multiple arch dams cross braced or strutted	3
Foundation grouting or drainage	8
Vibroflotation	1
Dams removed (some replaced by tanks)	4
Replacement dams constructed	9
Reservoirs maintained empty (some provide short duration flood detention)	7
Permanent storage restrictions	12
Storage restrictions until permanent improvement	36
Outlet works rehabilitations	3
Diversion conduits plugged	2
Total Improvements	132

Note: A single dam may have more than one improvement.

There has been only one use of vibroflotation and no other soil foundation improvement techniques have been used. The reason may be climatic. The construction season at most of the dams reviewed is 10 to 12 months, with high stream flows usually limited to 4 months. Also, about 25 percent of the dams reviewed are "off-stream", that is, the primary source of reservoir water is one of California's aqueduct systems which deliver water to and in drier parts of the state. These conditions mean that problem soils can usually be removed during initial dam construction or during rehabilitation.

The analyses used to determine the need for and to design the improvements have varied as much as the improvements themselves. Finite element analyses with acceleration time histories have been used on major or high hazard embankments and on most concrete dams. At the other extreme, the potential cost of finite element analyses has led to removal or lowering spillways of small embankment dams after minimal analysis.

The following sections briefly describe improvements to specific dams to illustrate the range of methods used and to point out important considerations in designing and constructing rehabilitations.

Stevens Creek Dam

A seismic stability reevaluation of Stevens Creek Dam completed in 1978 concluded that "the dam would not meet current performance criteria if subjected to the maximum credible earthquake - Magnitude 8 1/2 on the nearby San Andreas Fault". The fault is 2.5 miles from the dam. In addition, an analysis by DSOD in 1979 concluded that the spillway capacity was inadequate.

The compacted clayey sand embankment dam, located in the western part of "Silicon Valley", was constructed in 1935. The height and crest length are 120 feet and 1080 feet, respectively. The embankment was crudely zoned to place the most impervious material near the upstream face. A cutoff to the semi-indurated conglomerate and siltstone foundation is located beneath this zone. Up to 15 feet of relatively free-draining alluvium underlies the rest of the original embankment.

An embankment rehabilitation consisting of upstream and downstream soil berms was designed to limit strain potentials determined by cyclic triaxial testing and dynamic finite element analyses (Fig.1). Strain potentials computed for the central and downstream portions of the modified embankment and the alluvium were relatively low. The strain potentials for the upstream portion of the dam and the upstream berm exceeded 20 percent. This was taken to mean the upstream areas will probably be subject to spreading and slumping during the design earthquake. Post earthquake stability analysis of the remainder of the embankment, using post cyclic triaxial test results, indicated acceptable performance. A Makdisi-Seed

simplified analysis indicated a total deformation of approximately 10 feet. The chimney drain between the original dam and the downstream buttress is intended to act as a crack stopper as well as to keep the buttress from becoming saturated. Note that the downstream berm is 12 feet higher than the dam crest.

The capacity of the original side channel spillway was increased by extending the weir in an "L" shape. The weathered conglomerate and siltstone excavated for spillway enlargement was used in the berms. A 50-inch diameter outlet had to be lengthened to accommodate the berms.

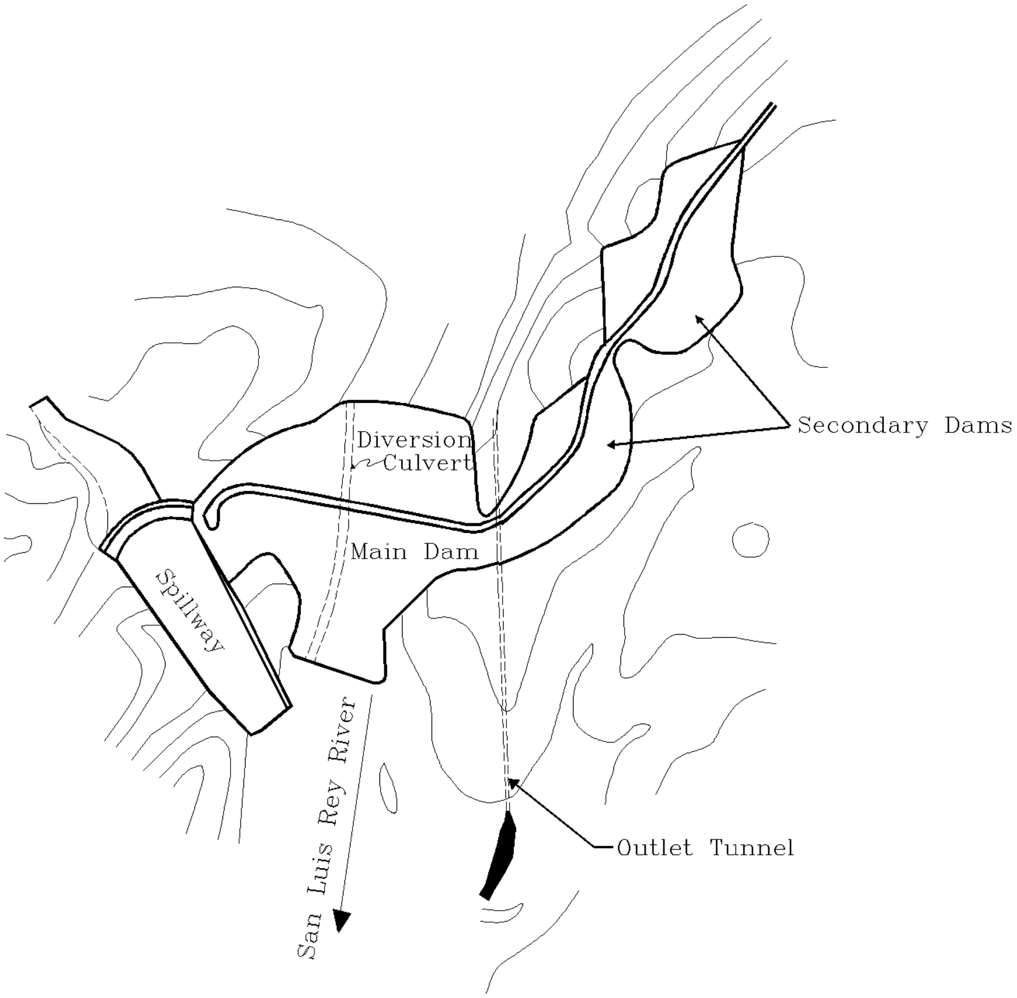
Stevens Creek Dam was 22 miles from the epicenter of the October 17, 1989, Magnitude 7.1 Loma Prieta earthquake. It was not damaged by the shaking which had an estimated peak ground acceleration of 0.35g. The reservoir was nearly empty at the time.

Henshaw Dam

Henshaw Dam, a hydraulic fill, (Fig.2) had another serious problem. It is located in the 8 to 12 mile wide active Elsinore fault zone. Traces of the fault trend diagonally under the main dam embankment (Bischoff 1985). The fault is deemed capable of producing a Magnitude 7.0 earthquake with potential fault rupture displacements, at the dam, of up to 5 feet in either the vertical or horizontal direction and or up to 7 feet in an oblique direction.

This 120-foot high dam, constructed in the 1920s, created a 204,000 acre-foot irrigation and municipal water supply reservoir on the San Luis Rey River in San Diego County. Preliminary studies showed the relative densities of the shell materials were low enough that liquefaction could lead to failure of the dam. They also disclosed the dam would be subject to piping should movement occur on the fault traces under the embankment. Later, concern developed that fault movement could raise a significant part of the reservoir relative to the dam and lead to reservoir release should the embankment severely slump.

Alternate reservoir sites were not available on the river and the choice of construction materials was limited in the broad fault zone. Operation studies showed that a 50,000 acre-foot reservoir would meet the owner's needs. The improvements selected were to permanently reduce the reservoir capacity to 50,000 acre-feet by constructing a 37-foot deep notch, 12-feet wide at its invert, in the spillway and to strengthen



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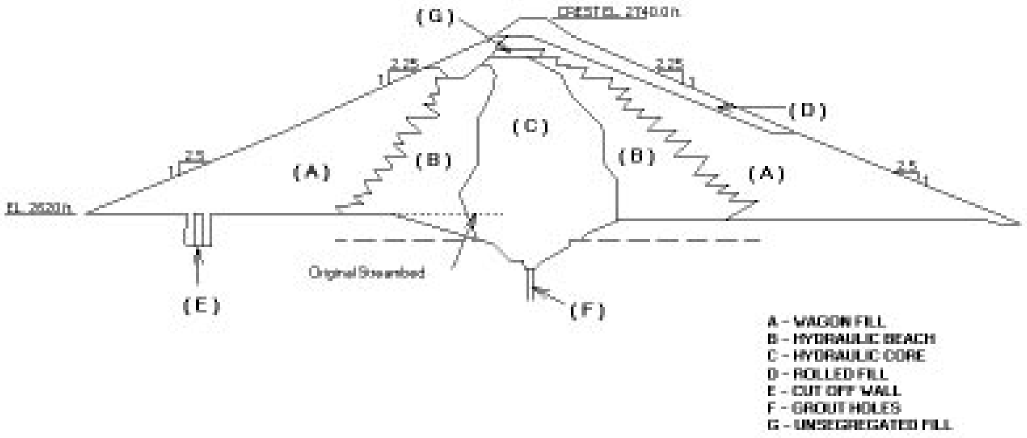
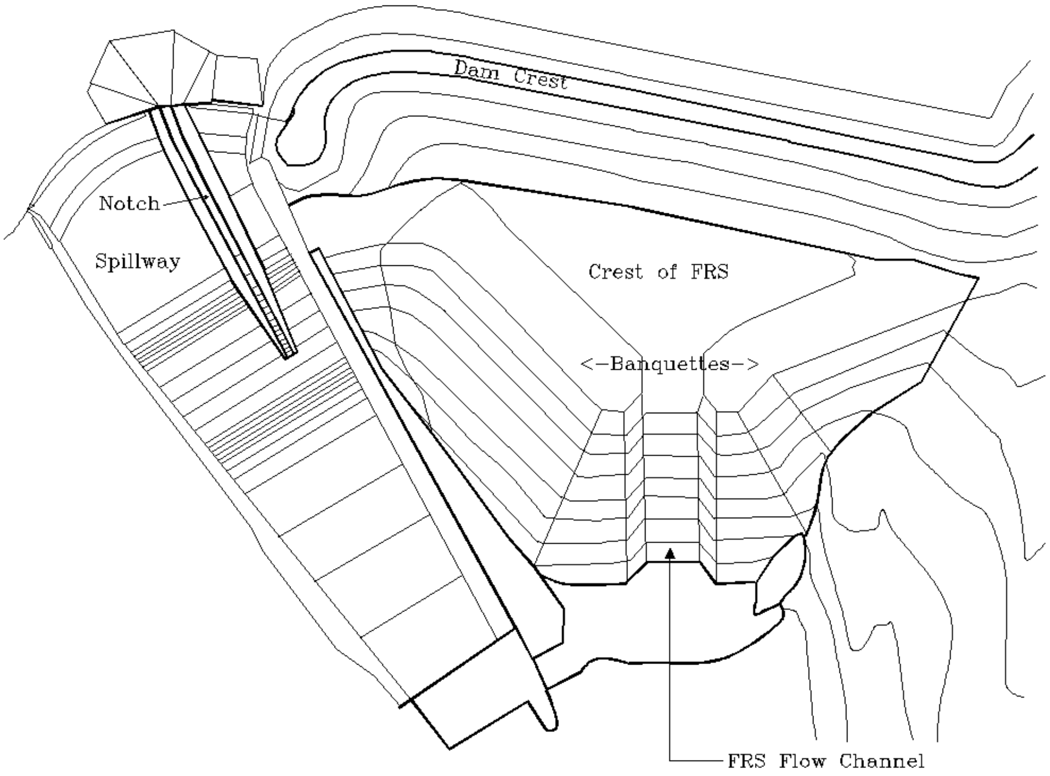


MAXIMUM SECTION

FIGURE 2 - HENSHAW DAM BEFORE MODIFICATION



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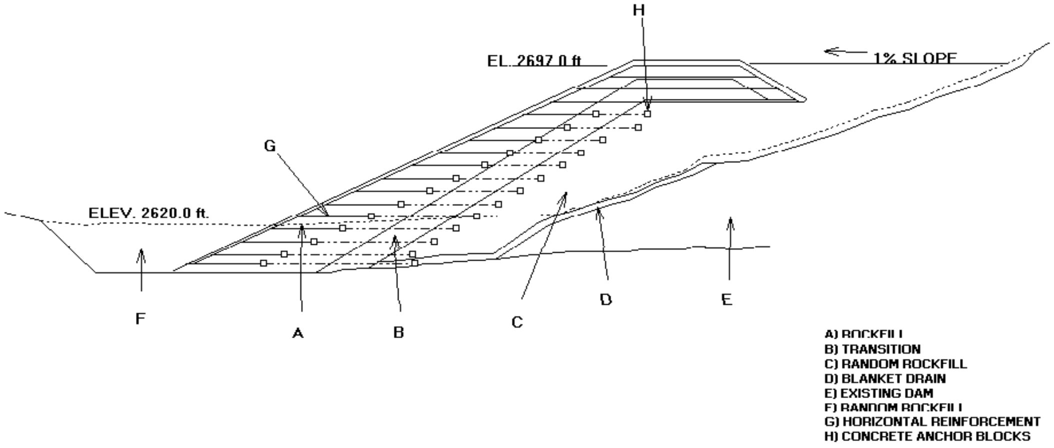

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FIGURE 3- HENSHAW DAM, FLOW RETARDING STRUCTURE (FRS)

the embankment by constructing a flow attenuating berm or Flow Retardation Structure (FRS) on its downstream face (Fig.3). The FRS also adds resistance to earthquake forces and fault movement. It was designed by pseudo-static analyses, using up to 0.3g.

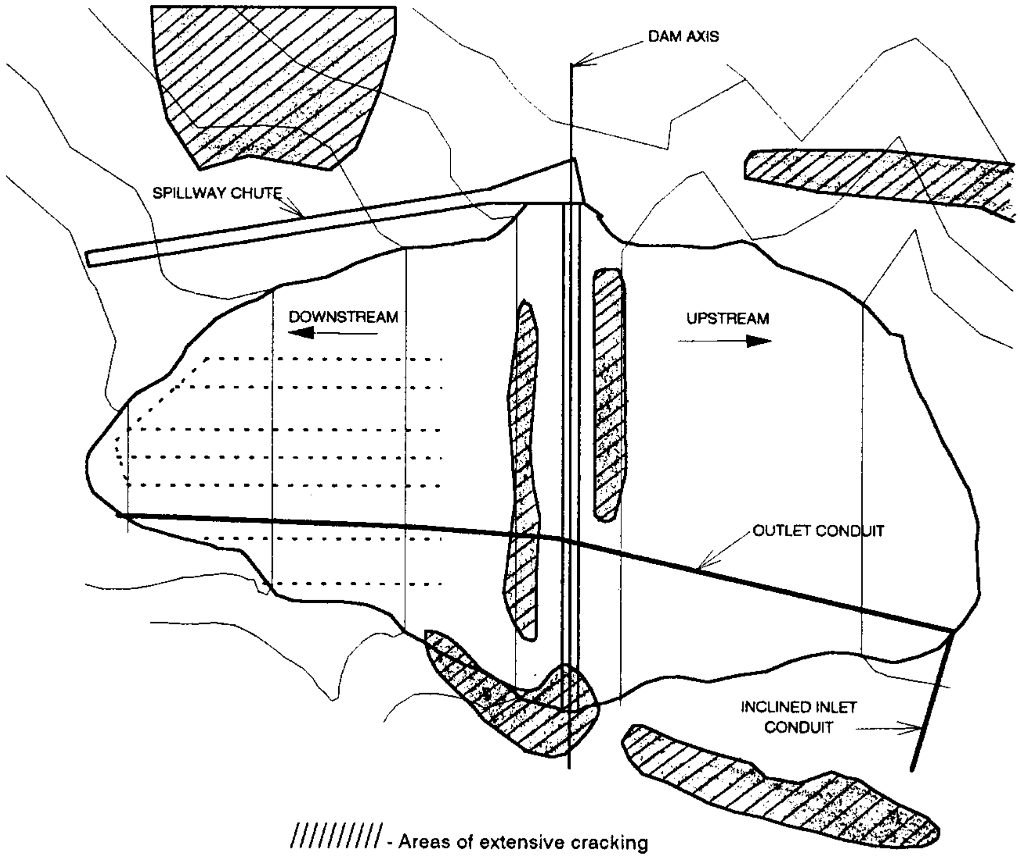
Lowering the reservoir level reduced the embankment phreatic line and the amount of material that can liquefy. Also, water is no longer impounded against the secondary dams, the slender part of the spillway and the narrowest parts of the abutments. Investigations for lowering the spillway disclosed some weaknesses in the structure, making the spillway rehabilitation a major project in itself.

The concept of the Flow Retardation Structure is to attenuate the release of water should the embankment fail by allowing it to flow through or over it. The top of the main portion of the FRS is 7 feet higher than the lowered spillway crest. The banquettes (berms) along the edges of the FRS are 10 feet higher to contain the potential overflows discussed above and moderate flood flows that might occur before repairs to earthquake damage can be completed. The surface and embedded reinforcement was designed to cope with sloughing or raveling of the rockfill under over topping or flow through conditions and to prevent deep-seated shear failure within the FRS.

Gravel and cobbles placed in the downstream end of a 10-foot diameter diversion conduit at the end of the dam construction were excavated and a 115-foot long concrete plug was placed under the FRS to seal potential leaks caused by fault movement.

Austrian Dam

The epicenter 0f the Loma Prieta Earthquake was seven miles from Austrian Dam. The 200-foot high, 700-foot long embankment dam was constructed in 1949-50 on Los Gatos Creek, near the town of Los Gatos (Fig.4). The design called for an upstream impervious zone, a downstream pervious zone, and highly pervious strip drains located near the old stream channel in the downstream zone (USCOLD 1992). However, the weathered sedimentary rock at the site broke down during excavation, placement and compaction, resulting in a nearly homogeneous gravelly, clayey sand embankment, compacted to approximately 90 percent of ASTM D-1557 maximum density. Most all soils and highly weathered rock were removed from the dam footprint prior to the embankment construction. The dam is in a vee-shaped



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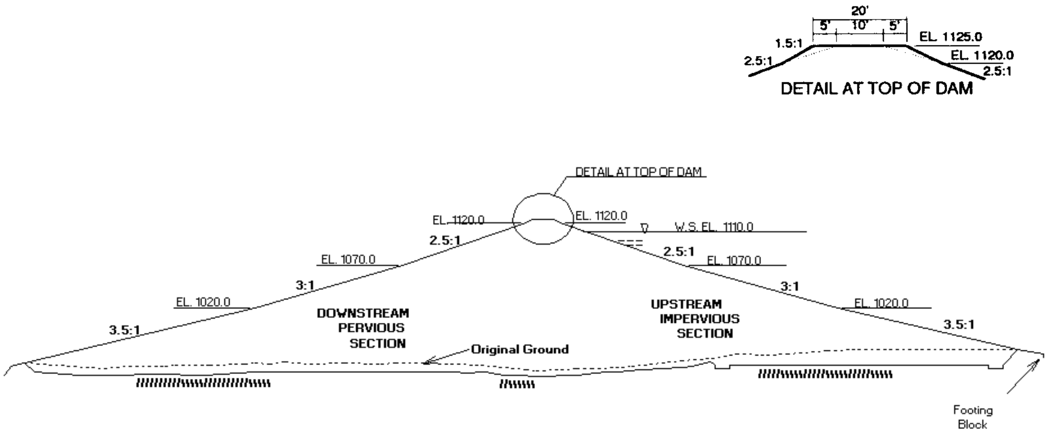

SECTION

FIGURE 4 - AUSTRIAN DAM

canyon in the Santa Cruz Mountains, about 2,000 feet northeast of the San Andreas fault zone.

The reinforced concrete outlet conduit, 4 feet in diameter, was constructed in a trench excavated into bedrock at the base of the left abutment. An inclined outlet facility extends up the left abutment, upstream from the dam.

The dam impounds a 6,200 acre-foot water supply reservoir. The dam crest is at elevation 1125. At the time of the earthquake the reservoir contained 700 acre-feet of water, which corresponds to a reservoir water surface at elevation 1023. Storage was low both as a result of the annual operating cycle and of three years of below average rainfall. Mid-October is the usual start of the local rainy season.

The earthquake caused a maximum settlement of 2.8 feet, with significant settlement occurring over the right three-quarters of the dam (Rodda et al 1990). Maximum downstream movement was 1.1 feet near the spillway wall on the right abutment, and maximum upstream movement was 0.4 feet at the left quarter point of the embankment. Longitudinal cracks up to 1 foot wide and 14 feet deep occurred within the upper 25 percent of the upstream and downstream faces. Shallower longitudinal cracks were found on much of the downstream face. Crest cracking was confined to the abutment contact areas. Transverse cracking and embankment separation from the spillway structure occurred to a depth of 23 feet and a maximum width of 10 inches. The separation was apparently due to a combination of soil structure interaction, embankment settlement along the very steep abutment and permanent wall deflection. A transverse crack was traced 30 feet down the left abutment, where the dam had been constructed on weathered, highly fractured rock.

The settlement and cracking at both ends of the dam crest was partially the result of low density embankment that was rapidly placed to top out the dam after the start of the 1950 rainy season. The difficulty of compacting between the spillway wing and return walls is also a probable cause of the settlement and cracking next to the spillway. Embankment construction on the poor rock on the upper left abutment was an acknowledged expedient to prevent the dam from over topping. An attempt was made to grout the foundation in this area immediately after the dam was completed.

A modified Seed-Lee-Idriss analysis for a M8.5 on the San Andreas fault was completed in 1981. The settlement prediction resulted in removal of a 2-foot high inflatable dam from the spillway. The damage by the M7.1 earthquake was probably more than inferred by the analysis, but the conditions described in the last paragraph are not modeled in such analyses.

Spillway damage consisted primarily of numerous transverse tension cracks. The structure appears to have elongated about one foot, toppling the end walls in the process. Some cutoff walls were damaged. Voids up to 6 inches wide were observed upstream from other cutoff walls. The walls of the "U" shaped section flexed inward, lifting the base of walls and adjacent portions of the floor slab up to one inch. The only damage to the outlet works consisted of the tipping of a valve actuator steel tank, located at the top of the inclined facility. Ground cracking occurred in and above the reservoir area and on the abutments.

Repairs to Austrian Dam began within days following the earthquake, so that the dam would not be over topped during the rainy season and could store water for use in 1990. Cracked embankment on the upstream face and embankment and foundation materials at the abutments were excavated and replaced with compacted embankment (Rodda and Pardini 1990). Crack stopper zones were included near the abutments (Fig.5). The grout curtain at the left abutment contact was regrouted. A toe drain was installed to improve drainage from the finger drains and provide seepage monitoring during reservoir filling. The cracks in the spillway were epoxy grouted to allow immediate use if needed. The spillway and earthwork repairs were essentially complete in about an 8-week period.

The owners were only able to accomplish this work because they owned land that could be used for borrow areas and had longstanding working relationships with the contractor and major suppliers. There was fierce competition for supplies, equipment, and experienced operators after the earthquake. Access to the dam was on damaged roads.

After not filling for three years after the earthquake the reservoir peaked at 2.5 feet over the spillway crest on January 22, 1993. The repaired spillway has held together. Close surveillance of the dam has been maintained each time new post earthquake reservoir levels have been reached.

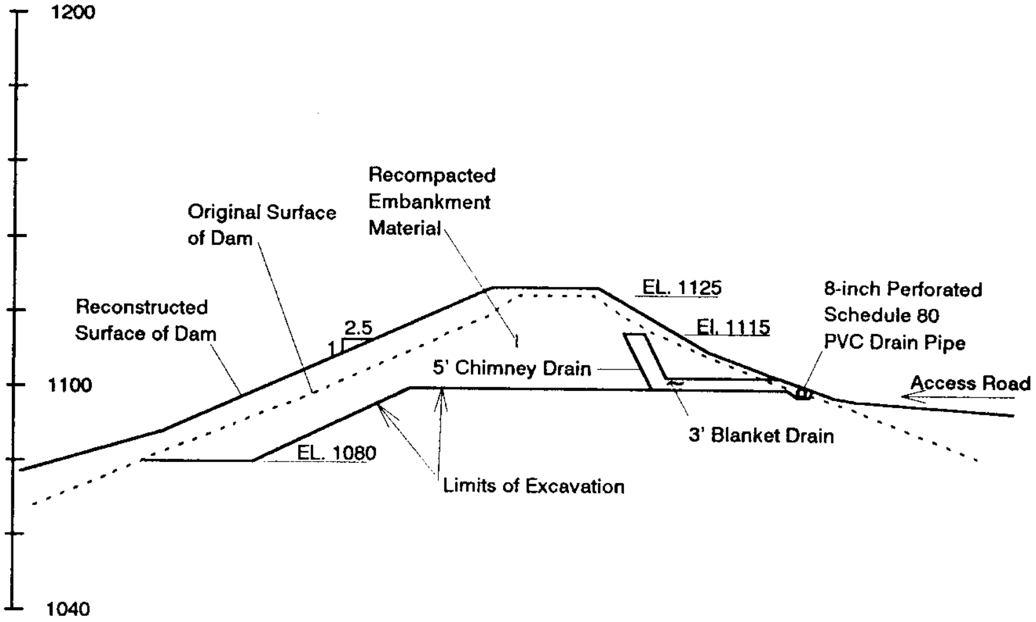

FIGURE 5 - EXCAVATION AND REPLACEMENT OF EMBANKMENT AT RIGHT END OF AUSTRIAN DAM

A replacement spillway is currently under construction on the left abutment where the rock quality is much better than the right abutment. The floor is being anchored into the rock for stability. The excavated materials are being placed on the lower portion of the downstream slope of the embankment. The crack stopper zones will be extended to the spillway wall on the left abutment and across the present spillway which will be removed near the dam crest. This construction will greatly improve the geometry of the embankment-spillway and embankment-abutment contacts. Grouting will be done on both abutments and is expected to lower the embankments phreatic line.

Bear Valley Dam

The epicenter of the M6.7 June 28, 1992 Big Bear Lake Earthquake was only 8 miles from Bear Valley Dam, a former multiple arch. The reservoir was full. There was no damage to the dam, which was rehabilitated in 1989 (Denning 1993). The arch bays were filled with mass concrete at that time. The local MCE for that design of the rehabilitation was a M6 at 1 mile.

Lower Crystal Springs Dam

Lower Crystal Springs, a 145-foot high gravity arch, was constructed on San Mateo Creek 15 miles south of San Francisco in 1888. It forms a 58,000 acre-foot reservoir in the San Andreas fault valley. The active trace of the fault is 300 feet upstream and parallel to the chord of the dam. Performance of the dam in 1906 during the M8.3 Great San Francisco Earthquake was excellent. In the 1970s, the dam's seismic stability was reevaluated. The dam itself was given a clean bill of health, but some of the appurtenances are being improved. One of them is discussed here.

Post-earthquake outlet operation is considered important for system operational needs and because of the potential for splinter faulting from the nearby active fault trace. Splinter faulting is defined as movement on minor faults or other planes of weakness caused by movement on the main fault. Reservoir drawdown would be necessary if these features create seepage paths through the moderately strong, weathered abutments.

Key elements of the outlet works have been improved to assure they are available if reservoir drawdown is necessary or alternately to hold the reservoir should the outlet towers be damaged (Bureau 1985). These elements are steel pipes in tunnels under the left abutment of the dam. The pipes, 54 and 78 inches in diameter, are supported on brick and concrete cradles respectively. They were otherwise unrestrained. They have been tied down with steel straps anchored to the floors of the tunnels.

Pigeon Pass Dam

Pigeon Pass Dam, a 30-foot high, 2900-foot long clayey sand embankment, forms a 912 acre-foot flood control reservoir in semi-arid Riverside County. The foundation is alluvium of various ages. The outlet is ungated, allowing the reservoir to empty within hours after rainfall ceases on the 9 square mile drainage area.

In December 1978, transverse cracks were discovered in the embankment. The causes of the cracks were determined to be a combination of embankment shrinkage and differential foundation settlement due to hydrocompaction and possibly seismic shaking. The largest crack was repaired by excavating and placing compacted embankment. The proximity of a nearby active fault, the San Jacinto at 4 miles, dictated that repairs include more than treating identified cracks. Cracks could rapidly reopen or new ones form in the rather brittle embankment during an earthquake, particularly where the dam is founded on cohesionless soils. A chimney drain was placed in a trench in the downstream slope to act as a crack stopper. Gallery drains were provided as outfalls from the chimney (Fig.6).

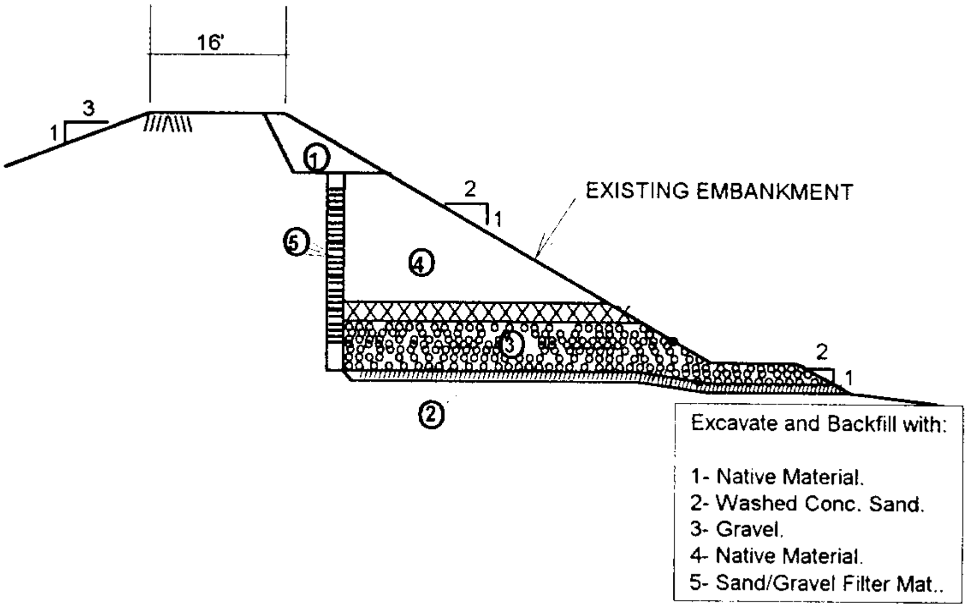

FIGURE 6 - PIGEON PASS DAM, CHIMNEY DRAIN INSTALLATION

The work was safely accomplished in a short time without the aid of trench supports. The chimney material is a well graded minus 1-1/2 inch concrete mix. It was dumped in place, wet, from ready mix trucks. The gallery material is 3/8 inch pea gravel; it is filtered by concrete sand.

Coyote Dam

Coyote Dam is a 140-foot high zoned embankment dam completed in 1936 across the known active Calaveras fault in southern Santa Clara County. The apparent active fault trace was mapped on the excavated foundation surface and a 50-inch diameter outlet conduit was aligned to avoid it. A control valve was installed at the upstream end so that the steel-lined reinforced concrete conduit would not be under pressure if it was ruptured by splinter faulting or a slight shift in the active fault trace.

When build-up of reservoir sediments after 30 years made operation of the control valve impractical for regulation, a valve was installed on the downstream end of the conduit. However, pressurization of the conduit was restricted to times when the contents of the reservoir could be captured by Leroy Anderson Reservoir located 3 miles downstream. When, in the late 1980s, continued accumulation of sediments necessitated another outlet modification, an outlet tunnel was constructed through the right abutment just above the level of the sediments. The new outlet tunnel is 200 to 300 feet farther from the active fault trace (Fig.7). The control valves are located upstream of a splinter fault crossing the tunnel alignment so that the tunnel is free flowing when crossing this feature. The tunnel is articulated into 10-foot long segments connected by water stops through the splinter fault zone.

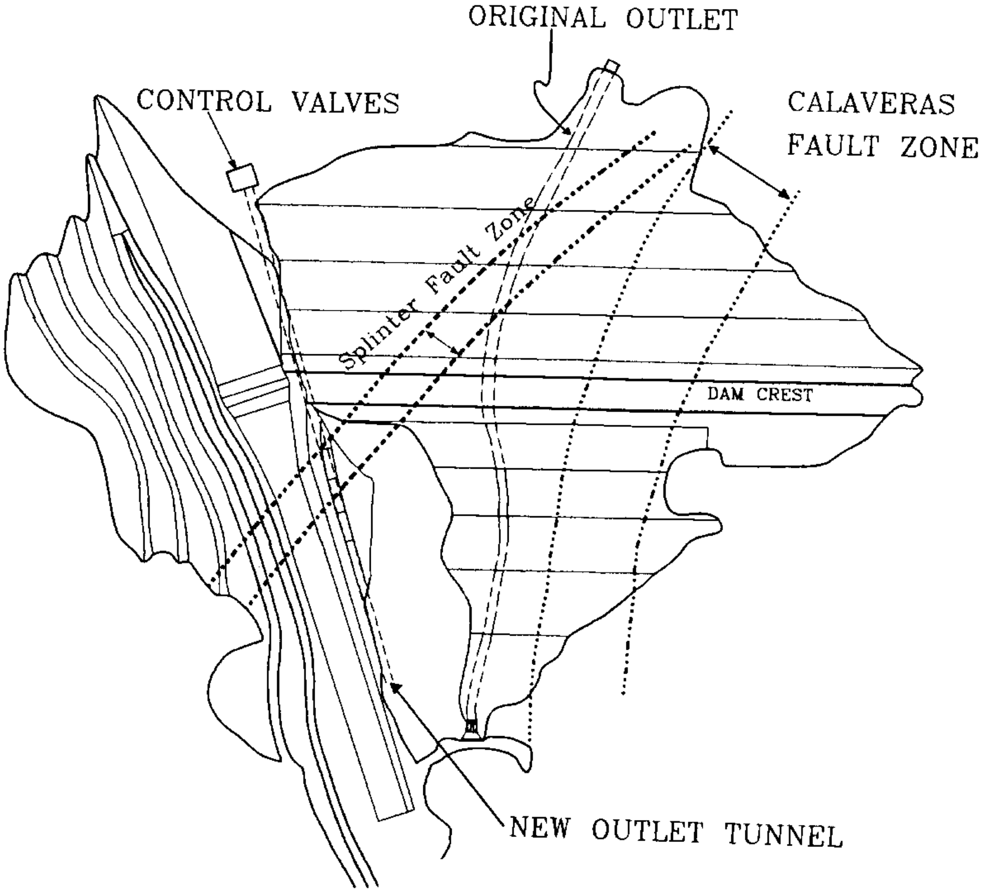

FIGURE 7 - COYOTE DAM, PLAN VIEW

While the new outlet virtually eliminates the conduit rupture hazard, DSOD is concerned about piping occurring through upper abutment and/or embankment cracking caused by fault movement. A reservoir operation scheme is being negotiated to ameliorate this concern by minimizing the time the reservoir is nearly full. Such a scheme is possible because the dam owner has the flexibility from operating several reservoirs, which are tied to conjunctive use of a major ground water basin.

Design Considerations

The need for buttresses, slope flattening and increases in freeboard is a direct product of stability and settlement analyses. The selection of important details is less obvious. James L. Sherrard (1967) provided guidance on these details in his report to the Department of Water Resources on "How should earth dams be designed differently in regions of earthquake activity?". The use of crack stopper zones and the general concern about the vulnerability of dam crests are, in part, a product of Sherrard's study.

Dams very near or across faults present special challenges. Splinter faulting is discussed previously under Lower Crystal Springs and Coyote Dams. Regional ground movement, as occurred at Hebgen Dam in 1959, was a consideration in rehabilitating Henshaw and other dams. Leps(1989) describes design and rehabilitation of dams directly across faults.

Storage Restrictions

As noted in Table 1, temporary storage restrictions have been used to improve the safety of 21 dams. These operating restrictions are placed soon after analyses identify stability problems. They allow time to design and finance repairs, find alternate water supplies and lately, to conduct environmental studies.

Reducing the allowable reservoir storage directly reduces the damage potential should an earthquake rupture the dam. It also reduces seepage pressures in dams and foundations and eliminates liquefaction potential where drainage of problem soils is complete. The engineers who do the stability analyses usually recommend the restriction depth.

Permanent storage restrictions are being used on only 12 dams. These restrictions can be difficult to maintain. Dam operators and regulators change and documents get lost. There is pressure to lift restrictions during periods of drought and other crises. If long-term restrictions are used, the conditions at the reservoirs must make the restrictions easy to maintain. Lowered or notched spillways are much more foolproof.

Emergency Response

California's dams have been tested by several earthquakes, the most notable being the 1971 San Fernando and the 1989 Loma Prieta. The experience has shown that dams must be made safe before earthquakes. There are too many obstacles to overcome to protect the public by detecting and treating earthquake damaged dams and implementing evacuation plans when they are needed. Some examples of actual obstacles with explanatory notes are:

> Key response personnel were not available. They had been injured or their families needed them.
>
> Communications were blocked. When telephone and radio facilities were not damaged, they were overloaded.
>
> Access to dams was difficult. Roads and bridges are designed to lower standards than dams. They should not be expected to survive earthquakes that damage dams.
>
> Repair materials, equipment and operators were in short supply. See "Austrian Dam".
>
> Helicopters were not available for inspections. News media and high level officials tied them up.

However, DSOD requires that dams have gravity outlets and that their operability be regularly demonstrated. Dam owners must provide dam break inundation maps to the State's emergency services office so that local jurisdictions can prepare evacuation plans. Each of these insurance measures has proven useful in dealing with emergencies at dams in California.

Two facets of the 1971 Lower San Fernando Dam incident should be considered in determining acceptable earthquake damage to dams: (1) The reservoir behind the damaged dam had to supply a large portion of the water for Los Angeles for two weeks while severe damage to the supply aqueducts was repaired. (2) A major public awareness effort was required to gain support for constructing Los Angeles Dam, the functional replacement for Lower San Fernando Dam (Phillips and Georgeson 1973). The new dam was constructed in the old dam's basin. The old dam was repaired and the area between the dams is maintained dry to provide double protection for the downstream area where 70,000 people were evacuated after the 1971 earthquake.

Conclusions

A wide variety of creative solutions have been used to improve the seismic stability of dams in California. Although there have been major advances in analysis techniques, the rehabilitations have not changed radically. Multiple arch dams are still being stiffened and embankment dams buttressed.

The performance of Austrian Dam during the 1989 Loma Prieta Earthquake reinforces concerns about damage to the tops of earth dams by earthquakes expressed by Sherrard.

Dams must be ready to withstand earthquakes. Provisions for emergency response should be treated as prudent insurance measures and not substitutes for pre-earthquake rehabilitation.

Reservoir storage restrictions can provide effective, rapid ways to increase dam safety, but can prove troublesome in the long term.

Acknowledgement

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Disclaimer

The opinions expressed are those of the author and are not positions of the Department of Water Resources.

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