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Seismic Analysis of Spinney Mountain Dam

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SYNOPSIS The Spinney Mountain Dam, now under construction in central Colorado, is a zoned earth embankment with a maximum height of 95 feet above foundation. Detailed geological investigations revealed rejuvenated sediments of nearby older faults, which have undergone tectonic movement within the past 13,000 to 30,000 years and hence are considered capable. Studies indicate the largest earthquake expected on the controlling fault would have a Richter Magnitude of about 6.2, implying peak ground accelerations at the site of about 0.6g and a 15-second duration of strong motion. Displacement on a branch of the main capable fault during such an event is estimated at four to six inches. Slope deformation analyses estimate a movement at the crest of the dam of not more than two inches horizontally and considerably less vertically, which would not result in a significant decrease in strength of the compacted soils. Reservoir induced seismicity is not considered to be a hazard.

INTRODUCTION

The Spinney Mountain Project, now under construction for the City of Aurora, Colorado, consists of a dam and reservoir for the City's water supply. It is located on the South Platte River in the South Park area about 130 highway miles southwest of Denver and about 2-1/2 miles upstream of Denver Water Board's Elevenmile Canyon Reservoir. Its purposes are to store waters originating west of the Continental Divide and diverted to the east slope via the Homestake Project, to allow full utilization of water available in the South Park tributary area, and to provide reserve storage for periods of extreme drought and during emergency outages of conveyance facilities of the Homestake Project.

The major features of the Spinney Mountain Project are shown in Fig. 1. They include a reservoir with an active storage capacity of 48,000 acre-feet and surface area of 2,520 acres; a 4,100-foot-long earthfill dam with a 25-foot-wide crest at El 8710, with a maximum height of 95 feet; service and auxiliary spillways; dam outlet works; Homestake diversion structure and conveyance channel; and waterfowl and recreation facilities.

The dam site is located in the Denver (South Park) Formation sediments. These rocks consist of interbedded sandstones, siltstones, claystones, and conglomerates, which strike in the general direction of the length of the dam and dip about 40° to 50° downstream. Detailed seismic investigations, unparalleled in Colorado, were performed near the site to determine potential for capable faults which would affect the design and construction of the dam. This paper presents the findings of these seismic investigations and analysis of the dam, and describes the related design and construction considerations.

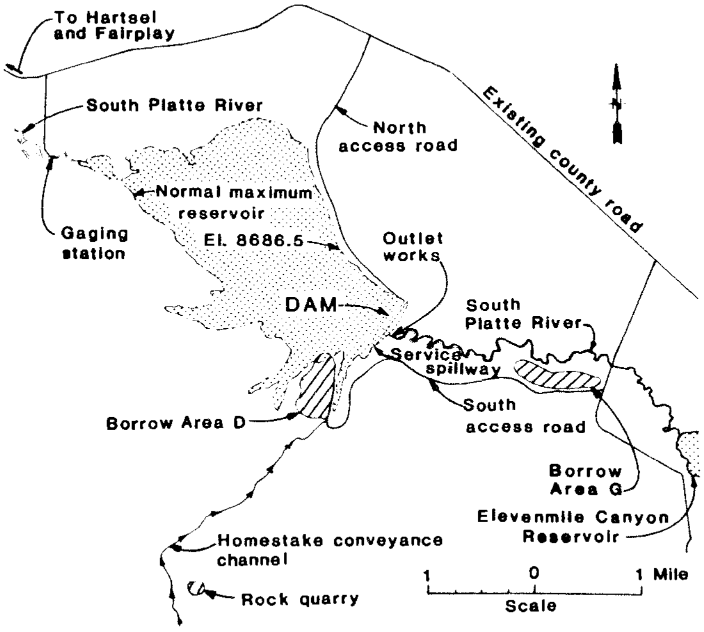


FIG. 1 PROJECT AREA

ASSESSMENT OF EARTHQUAKE RISK

General

The Spinney Mountain Dam is located in the southeast corner of a 40-by 60-mile topographic and geologic basin known as South Park. Historical earthquake reports over about the past century and reasonably complete seismographic data recorded since the mid-1960's, suggest the South Park basin constitutes a nearly aseismic area within a broader region of low-level seismicity.

Earthquakes of significant destructive capability are unknown in Colorado. However, the period of record is shorter than the interval between major earthquakes in some regions, such as parts of the mid-continent.

Ordinarily, structures in a historically aseismic region would be designed for minimal ground motion. However, a combination of increased regulatory awareness of seismic hazards, local concern, and a desire by the project owner to properly assess all factors related to dam safety, lead to performance of a reconnaissance-level geologic assessment of seismic risk at Spinney Mountain. The results of this preliminary study were surprising. Geologic evidence indicated a possibility of active faults in the project area. This unforeseen discovery prompted detailed study of the fault systems involved, and ultimately resulted in a more sophisticated seismic analysis and design of the dam itself.

Geologic Setting

A generalized geologic map and cross-section of the dam area are shown in Fig. 2. The dam foundation is underlain by interbedded Paleocene (55-65 million years old) sandstones, conglomerates, siltstones and claystones of terrestrial origin. Somewhat older Cretaceous marine sediments crop out north of the dam. Two major fault systems, each 20 to 25 miles long, pass within a mile of the dam site. Precambrian basement rocks were pushed up and westward over the sedimentary formations along the Elkhorn Thrust Fault, which generally parallels the east boundary of the South Park Basin. Subsequently, down-dropping of rocks to the east occurred along the Chase Gulch Fault, which locally cuts the Elkhorn Fault but is generally parallel and east of it. Although these fault systems appear parallel and distinct on the surface, geologic evidence indicates they merge into the same major crustal discontinuity at depth. Abundant regional evidence indicates major displacement of the Chase Gulch Fault occurred between about 30 and 40 million years ago, and that activity of the Elkhorn Fault ceased 45 to 50 million years ago.

Fault Investigations

The major, still-evolving technique for nonseismologic investigation of active faults is to search for geomorphic (land-form) evidence of geologically young displacement. One part of a general standard promulgated by the U.S. Nuclear Regulatory Commission (1975) and presented in several recent Corps of Engineers publications (e.g., Slemmons, 1977) classifies faults as "capable", i.e., potentially earthquake-generating, if they have undergone tectonic movement in the past 35,000 years. This standard was acceptable to the regulatory agencies involved in the Spinney Mountain Project and was adopted in the seismic hazard analysis.

Attention to seismic hazards in Colorado was focused by open-file reports of the U.S. Geological Survey (Witkind, 1976) and Colorado Geological Survey (Kirkham and Rogers, 1978). Several faults less prominent or more distant from the dam site than the Elkhorn or Chase Gulch were characterized in these reports as "potentially active," because they

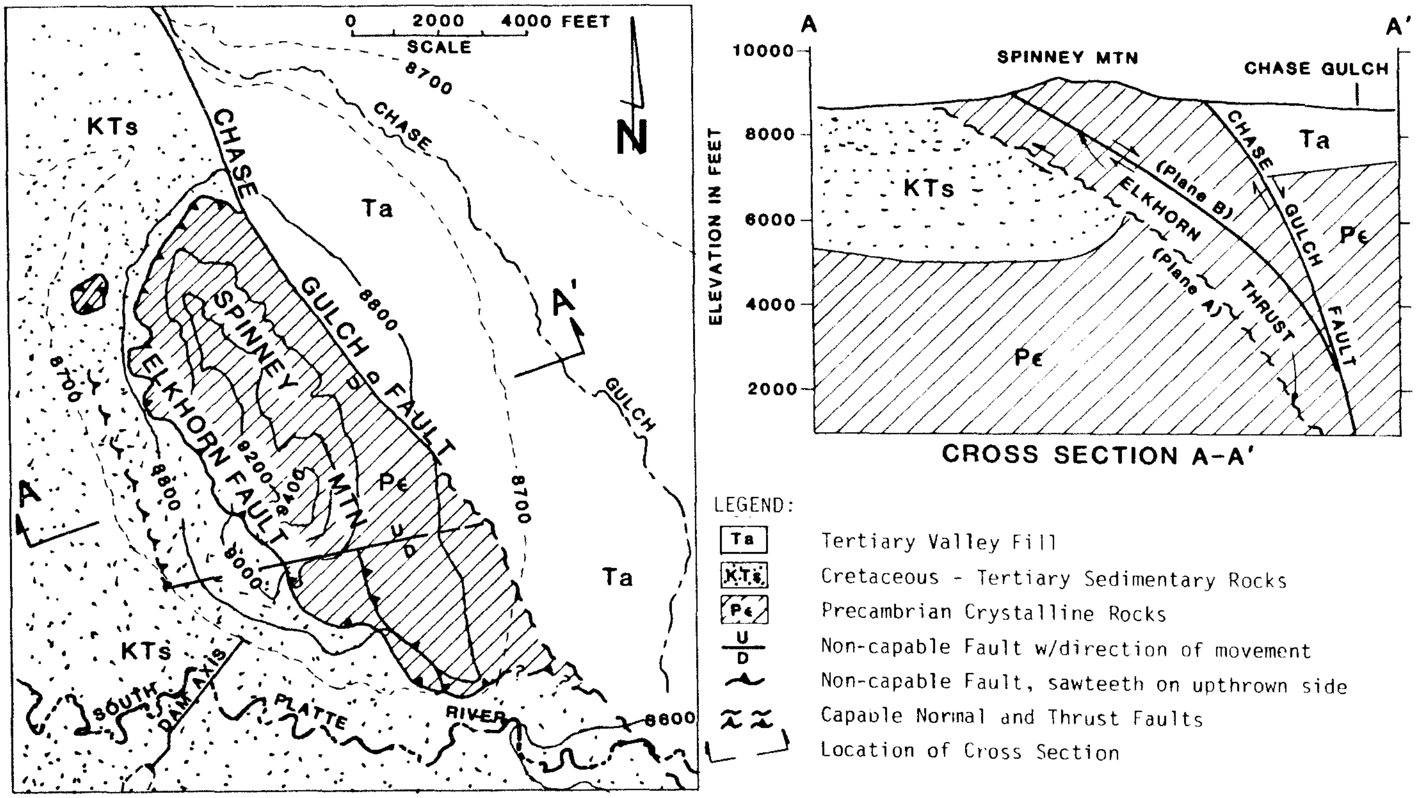


FIG. 2 GENERALIZED BEDROCK GEOLOGICAL MAP AND CROSS SECTION

were known to displace Miocene or younger geologic strata (less than about 20 million years old).

Initial field investigation indicated the major post-Miocene faults were not capable; however, it did reveal two very subtle, linear topographic scarps situated between one and two miles from the dam site, generally parallel to the traces of the Elkhorn and Chase Gulch Faults. Average topographic relief was about six feet, but erosion had so smoothed the scarps that they were virtually indiscernible on the ground. Depending on their geometry, however, both features showed clearly on aerial photographs taken either just after sunrise or just prior to sunset. Shallow trenching revealed that both features were in fact faults that offset both bedrock and unconsolidated alluvial deposits.

This wholly unexpected discovery prompted an extremely detailed geologic investigation designed to document:

1. The nature of fault displacement, i.e., tectonic vs. nontectonic.
2. The lateral extent of capable faults.
3. The magnitudes of displacements.
4. The age of last movement.

The complexity of these studies can only be discussed generally in this paper. During the first field season, it seemed that each new excavation or item of regional evidence added to the ambiguity of the analysis and that the indeterminacy of the problem forebode a genuine threat to the project. The successful conclusion of the seismic hazard study can be attributed to the thoroughness of the study and, equally important, to frequent communication with and field presentations for regulatory agencies. When the report on the evaluation by Converse Ward Davis Dixon, Inc., (1979), was finally submitted, state approval was prompt and complimentary.

Technical resolution of fault-related questions was achieved through synthesis of regional geologic and geophysical data, detailed surficial geologic mapping, drilling, geophysical exploration, and meticulous logging of over 1,300 lineal feet of trenches. Age relations were established by a combination of pedologic (soil genesis) and geomorphic methods and radiometric dating. It was determined that:

1. Fault displacements were in fact tectonic.
2. Maximum probable length of surface rupture was about 10 miles.
3. Fault offset within the past 35,000 years was on the order of eight feet.
4. Movement occurred between about 13,000 and 30,000 years ago, in addition to earlier activity.

The capable faults coincided with segments of the old Elkhorn and Chase Gulch Faults. They therefore merge at depth and form a single tectonic system. Renewed activity on the ancient faults was unrelated to stresses that caused their original displacement. A part of one of the minor "potentially active" faults identified by the Colorado Geological Survey appeared capable, possibly connecting with the system delineated near the dam site. Major regional faults suggested as "potentially active" by the Colorado and U.S. Geological Surveys showed no evidence of young displacement. This illustrates the necessity of thorough detailed field investigations.

The major remaining uncertainty regarding the capable faults is the number and magnitude of individual displacements. An immense effort would be required to resolve this question. It is nevertheless an extremely important theoretical consideration in that if movements on capable faults occurred as gradual, semi-continuous tectonic creep, damaging earthquakes would presumably not occur. Under the present state-of-the-art, it is more practical in most geologic environments to design for ground shaking than to attempt assessment of rates and magnitudes of individual fault displacements.

ESTIMATE OF GROUND MOTION FOR DESIGN

In the regulatory view, delineation of a capable fault using geologic criteria establishes the need for seismic design. However, geologic conditions cannot of themselves indicate the specific ground motions appropriate to such design. At Spinney Mountain, indirect geologic evidence suggested that capable faults did not extend into the dam foundation. However, that possibility could not be entirely discounted, and provisions were formulated to accommodate up to six inches of vertical or overthrust displacement. Groundshaking is the other major seismic design factor which is discussed below.

Probable earthquake magnitudes can be assigned to capable faults based on statistical relations between magnitude and fault length for earthquakes of record (Slemmons, 1977). Various relationships are available, depending on geographic groupings and fault characteristics. While perfect correlation has not been achieved, this remains the only practical technique for assigning ground motion parameters to a capable but historically inactive fault.

The 10-mile surface rupture length of the main capable fault at Spinney Mountain correlates statistically to a Richter Magnitude of 6.2. Standard attenuation curves (e.g., Schnabel and Seed, 1973) extrapolated on the basis of recent experience to distances as close as one mile from the causative fault, indicate a probable peak horizontal acceleration at the dam of about 0.6g. Duration of strong ground motion for such a tremor is expected to be about 15 seconds according to Bolt (1975).

SEISMIC EVALUATION OF DAM

General Method of Stability Analysis

The embankment stability was analyzed by the slip circle method (modified Bishop) using the computer program, STABL. Stability against earthquake forces was initially analyzed using a conventional pseudo-static analysis with a seismic coefficient of 0.1g. Determination of this seismic acceleration was based on the faults along the upper Arkansas Valley, some 30 miles from the site, which for a Richter Magnitude of 6.0 would require a design horizontal acceleration of 0.08g to 0.1g, according to Schnabel and Seed (1972).

There have been several examples, however, of dams which have failed which were considered to be safe based on a satisfactory pseudostatic analysis. This has given impetus to research and development to improve dynamic analysis of embankments, particularly following the failure of the San Fernando Dams during the 1971 earthquake in Southern California. The state-of-the-art of earthquake resistance design of earth dams is presented in the Rankine Lecture by H. Bolton Seed (1979). The two predominant current methods of stability analysis of earth embankments under seismic loading, are the more elaborate complete dynamic response method and the slope-deformation solution. The former is described by Seeds, Lee, and Idris (1975 and Seed, Makdisi and Dr. Allen (1978). Although there are variations of the dynamic analysis method, the more rigorous solution consists of determination of stresses by finite element analysis, dynamic laboratory tests, field tests both seismic and standard penetration, followed by the evaluation of probable performance. The slope deformation concept is based on the mechanics of a sliding block on a plane which was advocated by Newmark in the fifth Rankine Lecture in 1965). Newmark's method is based on a rigid body and is therefore considered conservative in determining estimated movements. Makdisi and Seed (1978) introduced a method which reduces the base or crest accelerations to effective average values for the full height of the dam, and in essence reflects some plasticity in the dam and results in considerably less deformation than the Newmark approach.

Considering the type and height of Spinney Mountain Dam, and the nature of the foundation, the slope deformation method was selected for seismic analysis of this dam using both the Newmark, and Makdisi and Seed methods, to bracket the potential movement. The method is also considered particularly applicable here since the embankment is constructed of clayey soils founded on a rock foundation, and no cohesionless materials are present in the embankment or its foundation which could be subject to liquefaction and would therefore warrant the more complex analysis.

Time History of Design Earthquake

Three recorded ground motions were selected as representative of the geological conditions at this site. Two of these records, Pacoima and Castaic, were obtained during the 1971 San Fernando magnitude 6.6 earthquake. The third record, Temblor, was obtained during the 1966 Parkfield magnitude 5.6 earthquake. The records were obtained on a computer tape from the Cal-Tech Earthquake Engineering Research Laboratory. Each horizontal accelerogram was scaled to three levels of peak acceleration (0.3g, 0.6g, and 0.67g) for the subsequent slope deformation analysis.

Slope Deformation Analysis

Newmark advanced the concept of permanent slope deformation as a rational alternative for evaluating embankment performance. In this method, the net resultant horizontal force on the sliding block considered in the analysis at any time, is the difference between the actuating dynamic force and the contact resistance on the plane surface within the embankment. Relative motion (sliding) will occur if and when the dynamic actuating force exceeds the internal resistance of the sliding plane. This internal resistance is based on a pseudo-static stability analysis which determines the horizontal yield acceleration based on the physical properties of the embankment zones. A horizontal yield acceleration of 0.16g was calculated for the Spinney Mountain Dam.

Slope deformation analyses were then carried out using both Newmark, and Makdisi and Seed, methods. The results as shown in Fig. 3 indicate that based on Newmark the crest of the dam would have a horizontal movement of less than 2 inches, and on the more realistic Makdisi and Seed method, about 1/10 of an inch. Based on these results it is the opinion of the authors that the proposed dam would

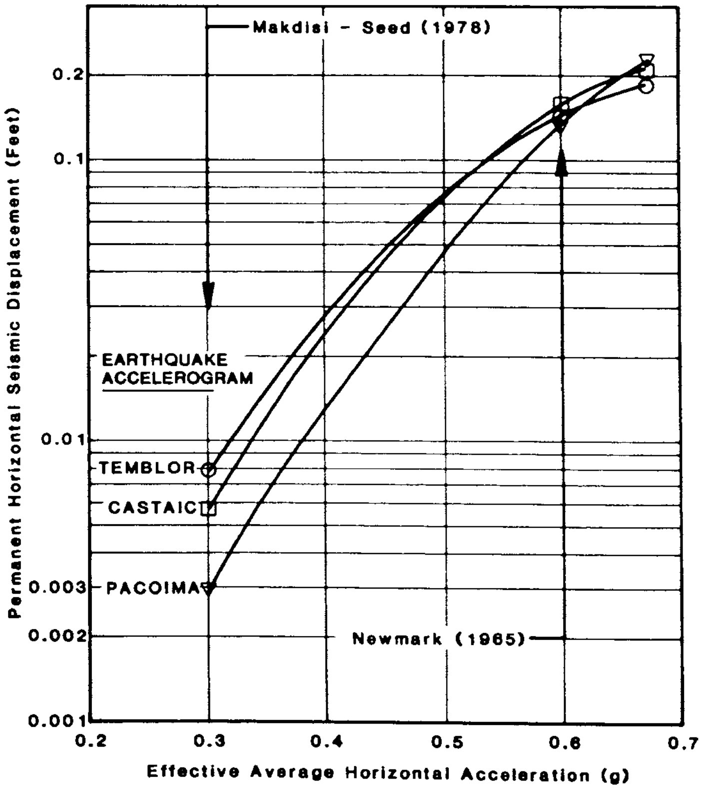


FIG. 3 SLOPE DEFORMATION RESULTS

spread horizontally less than 2 inches at each slope face. Some vertical movement would accompany this lateral deformation, but is expected to be a fraction of the horizontal values.

DESIGN AND CONSTRUCTION OF DAM

Design Section

A typical embankment section for the dam is shown in Fig. 4. The embankment is a multi-zone type with a chimney filter-drain leading to a horizontal blanket drain downstream. Sources of materials were chosen carefully so that each succeeding downstream zone meets filter criteria against migration of fines from the adjacent upstream zone. Zone 1 consists of impervious clays and Zone 2 also has low permeability. Zone 3 consists of silty and clayey sands which transition into the free draining sands and gravels of the Zone 5 filter-drain.

In the design of the dam it was planned that if a capable fault was discovered in the foundation, a Zone 8 of cohesionless "crack-stopper" materials would be located across the fault and extend 100 feet either side of the fault along the dam axis. It would be 10 feet thick and would extend horizontally upstream of, and 20 feet vertically along, the upstream face of Zone 1. The purpose of this cohesionless material is that in the event of a vertical displacement due to a foundation fault, which might be as much as six inches, the fines in the "crack-stopper" material would migrate to the core and fill the void, thus stopping or significantly reducing any leakage that may be associated with the displacement, and would effectively prevent the occurrence of erosion. However, no evidence of a fault was found during construction of the dam and hence the Zone 8 material was not produced. There was also a concern that the fine-grained Zone 1 and 2 materials might have dispersive characteristics. In the event of cracking of the fill due to an earthquake, piping of these materials would be more critical if they were dispersive and special sand filters would probably be required. Dispersive tests were therefore conducted of these materials and it was established that they do not have this characteristic.

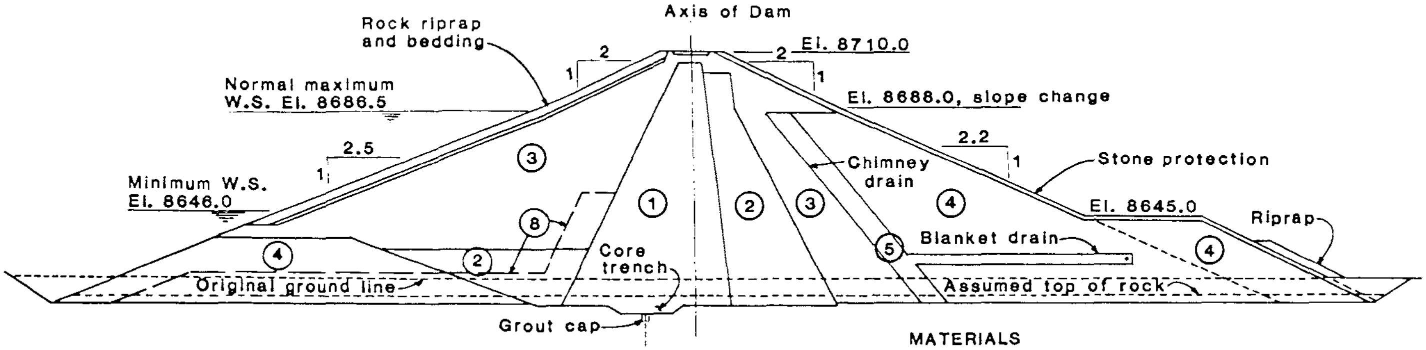
Features Providing Improved Earthquake Resistance

The dam embankment has characteristics generally recognized as providing inherently strong earthquake resistance, and the dam section was adjusted to improve this resistance ability. Several of the factors in this respect are:

1. It will have 23.5 feet of freeboard above normal high-water level.
2. The strength characteristics of Zone 1 clays plus the ample freeboard should prevent an open crack forming below the reservoir normal high-water level.
3. The section is a multi-zoned type with wide transition zones.
4. It has a positive drainage system with a chimney drain in the downstream portion of the dam. This chimney drain will ensure that the downstream Zone 4 shell is not saturated.
5. It has a wide plastic central core.
6. In case a capable fault was encountered in the foundation of the dam, a granular "crack-stopper" would be added in case of movement due to a major earthquake.
7. The topography of the reservoir basin is relatively flat obviating problems with large landslides.

Construction Control

The entire embankment is founded on rock of the Denver Formation. Construction control



MATERIALS

ZONE	FUNCTION	SOURCE	MATERIALS
①	Impervious	Borrow Area D-lower units-soils and weathered shales	Silty clays (ML, CL, CH)
②	Transition	Approved excavation material from spillways	Silty sands and clays (SM, ML, CL)
③	Upper shell	Borrow Area D-upper soil units	Silty and clayey sands (GM, SW-SM, SM-SC, SM, ML)
④	Lower shell	Approved excavation material from dam foundation	Sands and gravels (GP, SP-GP, SM, ML, ML-CL)
⑤	Chimney drain	Processed from Borrow Area G, 3" max.	Well graded sands and gravels
⑧	Crack Stopper	Processed from Borrow Area G, 1 1/2" max.	Well graded sands and gravels

FIG. 4 TYPICAL EMBANKMENT SECTION

parameters are shown in Table I. An engineering geologist inspected the dam foundation excavations as they were being made and the grout cap in the Zone 1 core trench was mapped geologically for its entire length. The purpose of this was to determine if any unusual features, particularly any faulting, were encountered in the excavations.

TABLE I - Summary of Compaction Specifications

Material	Compaction Moisture (% from optimum*)	Lift Thickness Compacted (Inches)	Passes Roller
Zone 1	+1 -3	6	12-Sheepsfoot
Zone 2	+1 -2.5	6	12-Sheepsfoot
Zone 3	+1 -2	9	12-Sheepsfoot
Zone 4	+1 -2.5	12	6-10 Ton Vibratory
Zone 5	As necessary	12	4-10 Ton Vibratory
Zone 8	As necessary		
Minimum Density Requirements:*			
Zone 1, Zone 2, Zone 3		Avg	>100%
		Not more 20%	< 98%
		None	< 96%
Zone 4		None	<100%
Zone 5, 8		None	<130.5 pcf dry density (70% relative density)

* Optimum moisture and maximum density determined by ASTM D 698.

CONCLUSIONS

Seismic investigations disclosed a fault considered to be capable about one mile from Spinney Mountain Dam, with an estimated length of 10 miles. This inferred fault length was statistically correlated to a maximum earthquake of Richter Magnitude 6.2. The maximum estimated horizontal rock acceleration at the proposed dam site is 0.6g from this earthquake. The estimated duration of the shaking is 15 seconds for this event.

Seismic analysis of the dam embankment was performed using the slope deformation analysis methods of Newmark, and Makdisi and Seed. Based on these results it was determined that the dam would spread out horizontally in the range of 1/10 to 2 inches at each slope face for the design earthquake. Vertical displacement would be a fraction of the horizontal values. Even a two-inch slope deformation will not significantly decrease the strength of the compacted embankment soils and the integrity of the earthfill dam would not therefore be significantly altered by strong ground shaking from the Magnitude 6.2 earthquake.

The dam embankment section has characteristics generally recognized as providing inherently strong earthquake resistance. Further, if a capable fault was encountered in the dam foundation it was planned to provide for a granular "crack-stopper" in case of movement (which could be as much as six inches vertically) due to a major earthquake. However, no such fault was encountered during construction. Reservoir induced seismicity is not considered to pose significant risk to the project because of the relatively low hydrostatic head and generally non-permissive geology and site conditions.

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