SEISMIC DESIGN OF CONCRETE-FACED ROCKFILL DAMS

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SUMMARY

This paper presents principles for seismic design of concrete-faced rockfill dams, the application to two dams, and defensive measures to mitigate seismic effects. The principles include: determination of design earthquake, design accelerograms, and material properties, and calculation of accelerations and deformations. Comparison of movements predicted for two dams to movements observed at similar dams implies that the methods used are conservative.

ANALYSIS PRINCIPLES

The primary analysis goal in the seismic design of a concrete-faced rockfill dam is a determination of the permanent deformations that an earthquake can produce in the embankment. The results of this analysis can be used to evaluate the potential for damage to the embankment, facing, and any critical structural elements.

The selection of earthquake motions beneath the embankment is the result of a site-specific seismicity study. Two major sources of potentially damaging earthquakes are generally investigated: 1) regional earthquakes, and 2) local earthquakes -- either can be the source of the most damaging earthquake. A special case of the second source is reservoir-induced seismicity (RIS) (Ref. 1). Procedures for selecting the design earthquake include the following: 1) Summarize accepted practice and seismic requirements for the site area; 2) Identify possible sources for earthquakes near the site and in the surrounding region; 3) Evaluate historical data for the site and the surrounding region, especially for the identified possible sources and for similar sources elsewhere in the world; and 4) Select the magnitude and epicentral and focal distances for the potentially most damaging earthquake or maximum credible earthquake (MCE).

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The design input accelerogram must accurately portray the most serious consequences of the design earthquakes. This can be achieved in the following manner: 1) Estimate the maximum acceleration at the site using attenuation relationships; 2) Estimate the natural period of the dam using empirical relationships or simplified procedures; and 3) Select an accelerogram from available earthquake records according to the following guidelines: a) Magnitude and epicentral and focal distances similar to the design earthquake; b) Maximum acceleration that will require little or no adjustment to match the design earthquake; c) Frequency content with no significant gaps and a relatively high response near the estimated natural period of the dam.

The selection of dynamic embankment material properties requires a determination of the rock type and the physical properties of the rock obtained from the quarry (e.g. gradation, angularity). Data from large-scale laboratory tests and field tests are available that will allow a sufficiently accurate determination of the low shear strain value of the shear modulus parameter K_2 under drained conditions (e.g. Refs. 2 and 3). (Drained conditions are generally assumed because positive drainage provisions prevent development of pore pressures in the rockfill.) Dynamic rockfill properties vary with confining stress and induced strain. These variations can be adequately approximated by empirical correlations based on data for sands (Ref. 4). Initial confining stresses are obtained from static finite element calculations.

The calculation of maximum accelerations of potential sliding masses can be made using a two-dimensional dynamic finite element code (Ref. 5) or published data (Ref. 6). The finite element calculation provides acceleration time-histories for the various points in the entire dam. From the results of the finite element analysis, a representative acceleration time history for any potential sliding mass is determined as follows: The sliding mass is divided into subsections and the accelerations of the subsections at a given time are averaged in proportion to the mass associated with each subsection. This produces an average time-history for the entire mass. The maximum average acceleration for each potential sliding mass is plotted against the ratio of the height of the lowest point of the mass to the total embankment height. If the results show significant scatter, they can be smoothed by drawing a curve, which is then used to scale the time-history for each sliding mass in proportion to the maximum from the curve for that mass. Published data for maximum accelerations of potential sliding masses can also be used to scale a representative time-history for the mass.

Finally, potential deformations in the embankment can be determined using a variation of the Newmark Method (Ref. 7). Any determination should account for the magnitude and length of time that a potential sliding mass is subjected to accelerations above its yield acceleration. (The yield acceleration is the pseudo-static acceleration that will give a factor of safety of 1.0 for a potential sliding mass.) Displacement values are computed by double-integration of the part of the acceleration time-history that exceeds the yield acceleration for each potential sliding mass. Permanent deformations at critical locations in the dam can be estimated using components of calculated deformations along potential slip surfaces near and beneath the desired location. Thus, maximum permanent deformations can be predicted for loss of freeboard, facing and transition zone shearing, downslope movements, and other movements of interest.

ANALYSIS OF TERROR LAKE AND CIRATA DAMS

Terror Lake Dam is a 50-meter high portland-cement concrete-faced dam being constructed on Kodiak Island, Alaska (Figure 1). Cirata Dam will be a 125-meter high, portland-cement concrete-faced dam in West Java, Indonesia (Figure 2). Both dams are major features in hydroelectric projects.

Due to the high seismicity in Alaska, two design earthquakes were chosen for the analysis of Terror Lake Dam. One design earthquake was chosen for Cirata Dam and was influenced strongly by the possibility of reservoir-induced seismicity. The design earthquake parameters for Terror Lake and Cirata Dams are as follows:

	Earthquake Data		Site Motion Parameters	
Case	Magnitude (RM)	Distance from Site (km)	Maximum Acceleration (g)	Predominant Period (s)
Terror Lake Dam				
DBE	8.5	25	0.35	0.50
OBE	6.5	6	0.50	0.28
Cirata Dam	6.5	9	0.35	0.35

Dynamic rockfill properties were selected and earthquake-induced accelerations in the dams were calculated. Several potential slip surfaces were selected and average induced acceleration time-histories were calculated for the potential sliding masses. For Cirata Dam, maximum accelerations of potential sliding masses were developed from finite element results; for Terror Lake Dam, published data were used. Integration with respect to yield accelerations gave the following displacements:

	Predicted Permanent Deformations (meters)		
	Terror Lake Dam		
Location	DBE	OBE	Cirata Dam
Decrease in crest elevation	0.6	0.2	0.3
Maximum displacement causing disruption of upstream face.	.9	0.3	0.6
Downstream slope	**	**	**

* Ravelling predicted.

COMPARISON OF PREDICTED MOVEMENTS FOR TERROR LAKE AND CIRATA DAMS TO OBSERVED MOVEMENTS AT SIMILAR DAMS

Key characteristics of the dams analyzed and of similar dams which have experienced major earthquakes are presented below along with earthquake parameters and predicted or observed movements:

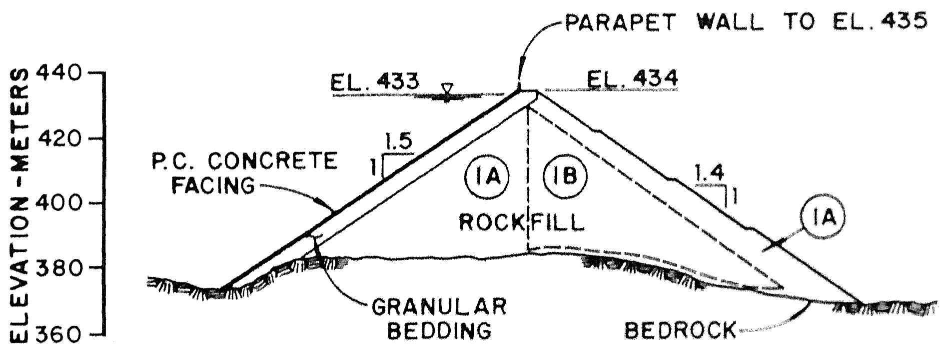

Figure 1 : TERROR LAKE DAM

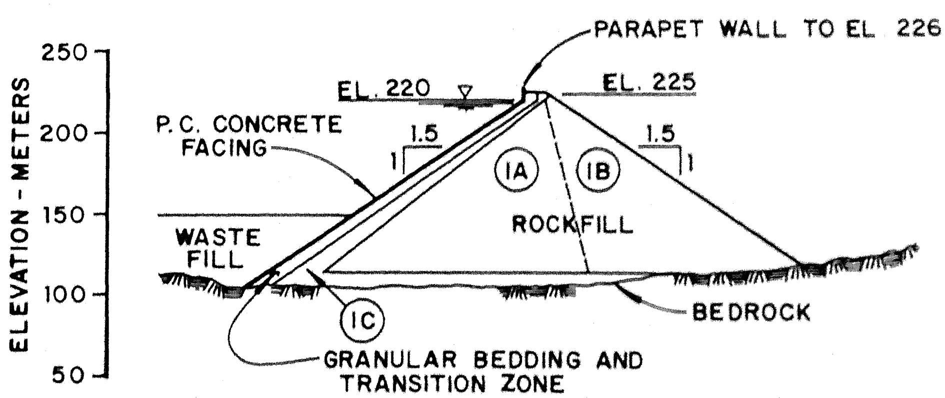

Figure 2 : CIRATA DAM

Dam and Characteristics	Earthquake & Magnitude	Site Intensity	Crest Movements Predicted
Terror Lake, Alaska			
50-m high	DBE (8.5)	a_{max} = 0.35g	0.6-m settlement,
1.5:1 U/S slope			0.7-m D/S movement
1.4:1 D/S slope	OBE (6.5)	a_{max} = 0.50g	0.2-m settlement,
Compacted rockfill			0.2-m D/S movement
Cirata, Indonesia			
125-m high	Design EQ (6.5)	a_{max} 0.35g	0.3-m settlement, 0.3-m D/S movement
1.5:1 U/S slope			
1.5:1 D/S slope			
Compacted rockfill			
			Observed
Cogoti, Chile (Ref. 8)			
75-m high	1943 (8.3)	VIII-IX	0.4-m settlement,
1.6:1 U/S slope		a_{max} = 0.15g	D/S slope slides
Dumped rock and gravel			
Malpasso, Peru (Ref. 9)			
78-m high	1943(Unk.)	VI	0.08-m settlement,
U/S placed - 0.5:1		a_{max} < 0.1g*	0.05-m D/S movement
D/S dumped - 1.33:1			

* Estimated from data for other sites.

The data are not directly comparable, because of simultaneous variation in embankment and earthquake characteristics. However, the following general comparisons are possible:

1. The settlement predicted for the 8.5 magnitude earthquake (a_{max} = 0.35g) is slightly larger than the settlement observed for the 8.3 earthquake (a_{max} = 0.15g).

2. The settlement predicted for the 6.5 magnitude earthquakes (a_{max} = 0.35 to 0.50g) are substantially larger than the settlement observed for the earthquake having an intensity of VI (corresponding a_{max} estimated at less than 0.1g).

DEFENSIVE MEASURES AND DESIGN CONSIDERATIONS

Terror Lake Dam, Alaska is located in a wildlife refuge and no one lives downstream of the dam. The seismic design is to prevent overtopping from a normal maximum pool in the event of a design earthquake. The crest width is 6.0 meters and freeboard is 2.5 meters from normal maximum pool to the top of the 1 meter high parapet wall, which is cantilevered from the concrete face slab. Expected damage resulting from a maxmimum earthquake with water at the normal maximum pool elevation is loss of support for the concrete facing above the pool elevation and parapet wall. Seasonal pool drawdown exceeds 30 meters. Should a maximum earthquake occur when the pool is low,the predicted damage is larger crest settlement with both upstream and downstream spreading of the upper portion of the dam. Reinforcing in the facing will limit crack openings and cause movements to be concentrated at joints. Waterstops near the top of the dam could be overstressed down to the vicinity of the reservoir water surface. Very little deformation of the upstream facing below the pool elevation is expected because water pressure restrains upstream movements. There is a 10-meter wide, well-compacted sandy gravel zone with a permeability of 10^{-4} cm/sec underlying the concrete facing. This material will prevent unsafe leakage from occurring as a result of possible cracking of the facing or opening of joints. The pool would be lowered and held down as needed during repairs to the face slab or crest.

Cirata Dam, Indonesia will be located upstream of another reservoir and a large number of people. The seismic design is to keep distress to a very low level in the event of a maximum earthquake. The crest width is 15 meters and freeboard is 6 meters. The granular bedding beneath the concrete facing has an intended permeability of 10^{-4} cm/sec and varies from 5.0 meters wide at the top of the dam and increases to 10.0 meters at the bottom of the maximum section. The bedding permeability and width is expected to prevent unsafe leakage due to any predicted deformations in the facing and embankment.

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