COMPARISON OF SEISMIC AND NONSEISMIC HAZARD EXPOSURE COSTS FOR A MAJOR WATER TRANSMISSION SYSTEM

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SUMMARY

Annualized hazard exposure costs for the three Mokelumne Aqueducts in a 25 kilometer length of their route within the San Joaquin Delta are estimated. The sources of hazard included flooding and static levee failure, potentially leading to failure of the Aqueducts, and seismically induced failures including dynamic failure of pipe supports or liquefaction of sandy soils in the foundation of levees adjacent to the Aqueducts. Vulnerability function of the system is then multiplied by unit repair cost to develop annualized hazard exposure cost for each failure scenario. The results show that seismic hazard exposure cost is several times greater than non-seismic cost.

INTRODUCTION

The three Mokelumne Aqueducts transporting water for the 1.1 million population of the east San Francisco Bay area pass through the San Joaquin Delta. In a 25 kilometer portion of this route from Stockton to Bixler, shown in Figure 1, the land is below mean sea level and is divided into a number of islands, each protected by a perimeter levee and surrounded by a system of navigable waterways. In this portion the pipelines go through the levees, under the rivers and are either underground or pile supported within the islands. Hence, in this section of the route, the Aqueducts are exposed to a number of non-seismic hazards (i.e., potential levee failure causing washouts, or long periods of inundation and corrosion if a broken levee is not fixed) as well as seismic hazards.

The investigations presented here were performed as a part of the planning studies of East Bay Municipal Utility District for the Mokelumne Aqueduct Security Plan and consideration of this plan into the general Water Action Plan.

Methodology

In evaluation of seismic or non-seismic exposure of any capital investments (buildings, reservoirs, refineries, lifelines, etc.) generally a five-step investigation is required. These steps are as follows:

• Evaluation of the susceptibility function of each system component to different intensity levels of each of the loading types.

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- Identification and quantification of the probability of exceedance of all potential sources of hazard (hazard intensity function) which might affect any component of the system.

- Evaluation of system vulnerability, i.e., evaluation probability of system failure given the component susceptibility and interdependence, and probability of exceedance of hazard intensities.

- Evaluation of the repair or replacement cost matrix for each component for different levels of damage intensity.

- And finally, evaluation of potential monetary losses, in terms of annual exposure loss, which should be added to other system costs (such as investment costs, operation and maintenance costs, etc.) and treated in the same manner.

Many investigators perform such studies only through the first few steps and express the results in terms of serviceability, reliability, and similar
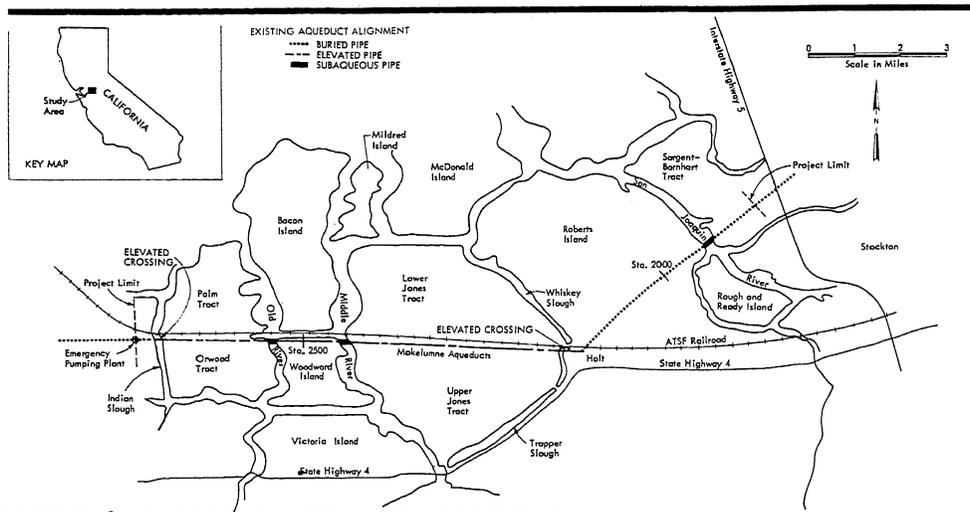
FIGURE 1. EXISTING AQUEDUCT ALIGNMENT THROUGH SAN JOAQUIN DELTA

factors. However, for proper planning for any capital investment, expansion, or rehabilitation, it is very important that all of the above investigation steps be completed and the results of probabilistic failure studies expressed in monetary units.

SYSTEM CHARACTERISTICS

The major components of the system in the San Joaquin Delta are: 1) the three steel aqueducts and their support system, and 2) the levee system surrounding and protecting the islands against inundation. Figure 1 shows the location of the pipelines on the islands and the type of support for each segment of the route.

The three pile supported steel pipes have diameters of 65, 67 and 87 inches and were constructed in 1929, 1949, and 1963, respectively. A typical support system provided at every 30 feet for the Aqueduct No. 1 (oldest) consists of a wood cradle resting on a concrete bent which is shear pinned and supported on two wood piles. The newer aqueducts rest on a strap steel cradle supported by a hinged swivel joint structural system on a concrete pedestal resting on four battered concrete piles. The major concern in continued functioning of this component of the system was judged to be the lack of dynamic stability for Aqueduct No. 1. A secondary concern was potential for dynamic failure of the piles should the foundation soils liquefy.

To evaluate the dynamic lateral resistance of the system a comprehensive investigation program was performed (Refs. 1 and 2). Core samples of the timber piles of Aqueduct No. 1 were obtained at and near the shear pin supports. The samples were examined for decay and bacteria attack and also tested for shear resistance. To evaluate dynamic lateral pile resistance, a program of drilling and testing of the subsoils along the pipeline route was first performed (Refs. 3 through 6). Then, two-dimensional finite element models of typical soil-pile-structure systems were formed using computer program FLUSH (Ref. 7). Then the seismic record of a ground motion taken at a site with relatively similar geologic profile (the Ferndale record of 1954 earthquake) was selected, deconvoluted to bedrock, and then applied to the base of the finite element model of the site. Amplitudes of the motion were varied to result in a peak ground acceleration of 0.10, 0.15, 0.20 or 0.30 g and response of the model for each case was computed. Potential for liquefaction of sand and/or extensive deformation of peat layers causing lack of lateral support for piles were computed. Finally, the potential for seismic failure of each of the aqueducts for each level of ground acceleration were evaluated. The results are presented in Table 1.

The other major component is the system of levees which surround and protect the islands along the route against inundation. To evaluate potential levee failure due to existance of peat or other soft soils, a geotechnical investigation program including drilling, sampling, laboratory testing, and stability analyses was undertaken. Profiles of soil conditions and properties for all levees and levee crossings whose failure could affect the aqueducts were developed (Refs. 3, 4, and 5). The factors of safety by conventional methods (modified Bishop) were then calculated for all critical stations along the levees. Since the soils in the levees and their foundations are non-engineered and were found to have highly variable properties, the dependence of the calculated factor of safety on the strengh variation of soils was calcu-lated. From this study, the probability of failure associated with each calculated safety factor was assessed. The results of these evaluations are presented in Table 1.

SOURCES OF HAZARD

The major non-seismic source of hazard which could affect the aqueducts is the potential static levee failure. There have been over 50 case histories of levee failure within the San Joaquin Delta during the past 40 years. The potential for levee failure also increases as the floor of the islands subside at a rate of 5 to 7 cm annually due to decomposition of the peat and wind erosion. Past levee failures have caused erosion scours as wide as about 500

TABLE 1

ANNUAL HAZARD EXPOSURE PROBABILITIES OF THE EXISTING AQUEDUCT CONFIGURATION

I. ANNUAL NON-SEISMIC HAZARD EXPOSURE PROBABILITIES:

Flood Stage (ft,MSL)	Annual Probability of Flood Stage	Expected No. of Islands of Tracts Inundated	Probability of Aqueduct Failure by Scour
<5.0	0.580	None	0.00
5.0-6.0	0.272	0.5	0.07
6.0-7.0	0.110	2	0.26
7.0-8.0	0.028	3	0.36
>8.0	0.010	More than 3	0.65

II. ANNUAL SEISMIC HAZARD EXPOSURE PROBABILITIES:

Acceleration Level, g	Annual Probability of Acceleration Level	Expected # of Islands or Tracts Inundated	Probability of Aqueduct Failure by Scour	Expected # of Elevated Aqueduct Breaks			Expected # of Buried Aqueduct Breaks	Expected # of Subaqueous Crossings Failed
				No. 1	Nos. 2 & 3	Total		
<0.05	0.850	None	0.00	0	0	0	0	0
0.05-0.10	0.090	0.5	0.07	10	0	10	0	0
0.10-0.15	0.025	1	0.14	15	10	25	1	0.5
0.15-0.20	0.019	3	0.36	Destroyed	30	No. 1 + 30	3	1
0.20-0.25	0.012	More than 3	0.65	Destroyed	60	No. 1 + 60	10	2
>0.25	0.004	All	0.65	Destroyed	Destroyed	All	More than 10	All

feet and as long as 1,000 feet. Hence, levee failures within this distance to the aqueducts could potentially cause failure of the pipelines.

To quantify this hazard, the records of past levee failures within the San Joaquin Delta were gathered and synthesized (Ref. 8). From this evaluation, it was concluded that: a) there is a direct relationship between the number of failures (per mile of levee) and the thickness of the layer of peat under the levee, and b) about one half of all past failures have been due to overtopping and hence directly proportional to the probability of the flood stage in the adjacent rivers and waterways.

To evaluate the probability of flood stages in the waterways surrounding the islands along the Aqueduct route, data from the staff gages of the U.S. Army Corps of Engineers (Ref. 9) for the nearby stations were obtained and analyzed. The recurrence intervals and the corresponding annual probability of occurrence of different flood stages were then calculated. The results are presented in Table 1 and Figure 2a.

For probabilistic seismicity evaluations, all of the past earthquake data and literature on the active faults within a 100 kilometer radius of the site were first gathered and reviewed. Seismicity of the site, in terms of annual number of occurrence of different levels of peak ground acceleration, were then calculated after Ref's (10) and (11). With either method, two attentuation relationships of Housner (Ref. 12) and Schnabel and Seed (Ref. 13), both modified in light of recent data (Ref. 14) to account for the very deep sedi-

ments at the site were used. The results were also checked against a more
recent evaluation of seismic probability in California (Ref. 15). As a result,
a rather wide range of values varying by about one order of magnitude was
obtained. Then in a meeting with Profs. B.A. Bolt and H.B. Seed, a singular
curve within the range was selected to be used for quantification of seismicity
of the site. The acceleration density function is given in Table 1 and Figure
2b. Since faults capable of generating magnitude 8 or greater

(a) ANNUAL PROBABILITIES
    OF FLOOD STAGES

(b) ANNUAL PROBABILITIES OF
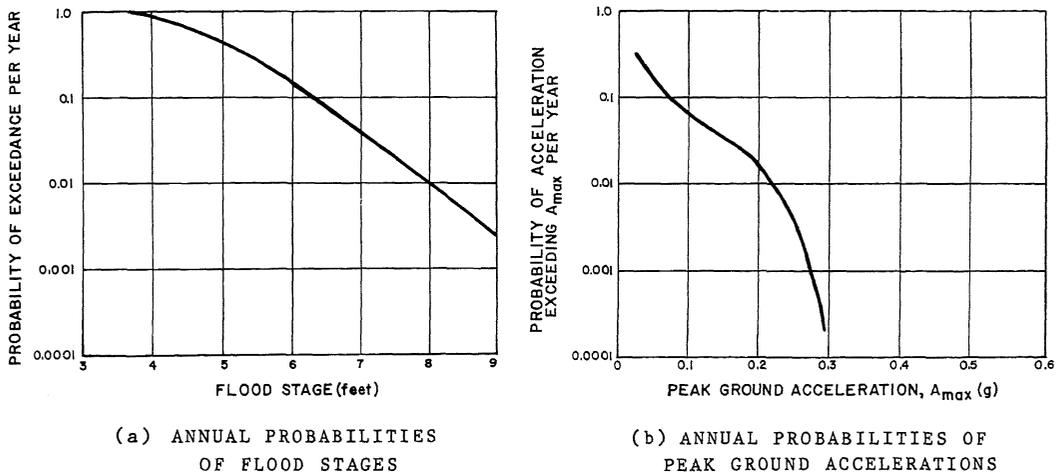   PEAK GROUND ACCELERATIONS

FIGURE 2. PROBABILITIES OF EXCEEDANCE OF NATURAL HAZARDS

earthquakes are distant to the site, the critical earthquakes affecting the
site are of magnitude 6 to 6.5. Hence, no attempt was made to break the
acceleration density function into its joint probability of accelera-
tion/magnitude matrix.

SYSTEM VULNERABILITY

The Aqueducts have performed quite satisfactorily in the past and are
expected to do so in the future. They have resisted ground accelerations as
high as 0.05g (Livermore earthquake of 1980) and they have survived the failure
of the ATSF railroad embankment in 1980 which caused an erosion scour to within
one meter of the tip of the piles. However, they have not yet been subjected
to a severe ground shaking or a direct levee failure at a crossing. Hence,
quantifications of the system vulnerability, defined here as annual probability
of failure, becomes highly judgmental.

The results of the analyses are presented in Table 1 which gives: a) the
probability of inundation of islands and aqueduct failure as a function of
non-seismic levee failure, and b) probabilities of different modes of failure
as a function of peak ground acceleration.

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DAMAGE - COST OF REPAIR

The cost of repair for each scenario of failure was calculated. For scenarios involving levee failure, it was assumed that the District will burden half of the cost of levee repair and the other half would be paid by other concerned parties. In addition, a contingency factor of 10 percent for two

TABLE 2 -- COST OF REPAIR

Scenario	Costs ($1,000)
Levee Failure	2,500
Levee Failure at Crossing	10,000
Aqueduct Failure (Buried Section)	425
Aqueduct Failure (Elevated) #1	1,325
#2	375
#3	525

simultaneous failures and 25 percent for three or more failures was assumed. The repair in general was assumed to be replacement-in-kind. However, for multiple failure scenarios it was assumed that maximum repair cost could not exceed the cost of construction of two new 86-inch diameter pipelines having the same capacity as the existing system. This cost was considered to be the maximum limit of damage, which was found to be about $212 million. The results of cost estimations are summarized and presented in Table 2.

ANNUAL HAZARD EXPOSURE COST

Summing the products of damage for a given intensity of hazard times the annual probability of occurrence of that intensity would give the annual hazard exposure cost. This was done for the non-seismic and seismic hazards of the existing Mokelumne Aqueducts. The results are presented in Table 3. As can be seen, the annual non-seismic hazard exposure cost is approximately $1.5M, whereas, the seismic hazard exposure cost is $6.2M. Hence, it is concluded that for the system described, exposure cost for seismic events is almost 4 times greater than non-seismic events.

ACKNOWLEDGEMENT

TABLE 3

ANNUAL HAZARD EXPOSURE COSTS – EXISTING AQUEDUCT CONFIGURATION

(All costs in $1,000 at July 1981 price levels)

I. ANNUAL NON-SEISMIC HAZARD EXPOSURE COSTS

Flood Stage	(A) Annual Probability of Flood Stage	Expected Cost (Inundation)	Expected Cost Scour	(B) Total Expected Annual Cost	(A x B) Annual Hazard Exposure Cost
<5	0.580	$ 0	$ 0	$ 0	$ 0
5 - 6	0.272	1,250	170	1,420	386
6 - 7	0.110	5,500	640	6,140	675
7 - 8	0.028	9,370	890	10,300	288
>8	0.010	18,800	1,600	20,400	204
					$ 1,553

II. ANNUAL SEISMIC HAZARD EXPOSURE COSTS

Acceleration Level, g	Annual Probability of Accel. Level	(C) Expected Cost (Inundation)	Expected Cost Scour	Expected Cost (Elevated Breaks)	Expected Cost (Buried Breaks)	Expected Cost (Crossings Failed)	(D) Total Expected Annual Cost	(C x D) Annual Hazard Exposure Cost
<0.05	0.850	$ 0	$ 0	$ 0	$ 0			
0.05-0.10	0.090	1,250	170	13,200	0	$ 0	$ 0	$ 0
0.10-0.15	0.025	2,500	350	24,400	425	0	14,600	1,320
0.15-0.20	0.019	15,600	890	50,700	1,300	5,000	32,600	815
0.20-0.25	0.012	56,200	1,600	64,200	4,250	10,000	78,500	1,490
>0.25	0.004	212,000	–	–	–	20,000	146,000	1,750
							212,000	848
								$ 6,223

*Replacement of existing aqueducts with Double Elevated Aqueduct.
(Inundation of right of way)

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