SEISMIC RELIABILITY ANALYSIS OF WATER FILTRATION PLANTS

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SUMMARY

A systematic procedure is presented for assessing the seismic reliability (or risk) of complex, single-site water facilities. The approach is based on resolving the operation of the facility into a network of nodes and links. By analyzing the reliability of these individual components, one can assess the overall reliability of the plant using standard Boolean techniques. To demonstrate the procedure, an example is provided for a specific water filtration plant.

INTRODUCTION

The seismic analysis of water supply systems has primarily focused on the performance of underground pipes. The reliability or risk to more complex single-site facilities, such as water filtration plants, has generally been ignored or oversimplified. The purpose of this paper is to introduce a procedure for evaluating the seismic reliability of these facilities. The approach is demonstrated on a water filtration plant but can be generalized to less complicated facilities such as pumping plants. The approach subdivides the filtration plant into nodes and links that pertain primarily to the flow of water through the plant itself. Data on the seismic vulnerability of such nodes and links can then be used to estimate reliabilities of such nodes and links at various levels of ground shaking. These probabilities can be combined using Boolean techniques to estimate the probability of maintaining water flow throughout the plant.

APPROACH

For illustrative purposes, this analysis is applied to a specific treatment plant. The main operation emphasized is that which pertains to the flow of water. Other systems, such as chemical, power, electrical, and telemetric, are not analyzed here, although they could be using the same set of procedures prescribed here for the water flow analysis.

Characterization

Figure 1 provides a perspective drawing of the plant with some main nodes identified. Major flows enter A from S_1 (an aqueduct), and then proceed through the plant. Bypass capability from A to H (the outlet), is available, but without chlorination capability. Flows from a creek (S_2) enter C, (screen house) which is specially needed for debris in the spring and the

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fall. S_1 *is the major source*, with variable flows from S_2, which naturally provides more water in the spring.

Ⓑ (inlet control building) leads to aeration channels and the mixing area, where the flows enter coagulation and mixing basins. Ⓓ' has been used to denote the points of connection between such basins and the aeration channels and the mixing area. Ⓓ (chemical building), does not actually comprise a node or link in the system of water flows, although chlorination piping and other conduits connect various systems with Ⓓ to other parts of the plant. Hence, Ⓓ must here be analyzed separately from the main flow of water.

Water flows from the coagulation and sedimentation basins to filter basins at Ⓔ. In this plant there are ten coagulation and sedimentation basins and ten filter basins. As a result, barring considerable permanent displacement, it is unlikely that all channels would be damaged in an earthquake. Even if several basins are damaged, those can be valved and repaired while flows continue in the other available channels. However, in filtration plants with far fewer basins, basin damage would be more likely to lead to plant closure than in the plant in Figure 1.

From the filter basins, water flows into the pipes in the pipe gallery area and to a postchlorination area, one of several points connected by piping to the chemical building so that chlorine can be added. From this area, generally designated Ⓕ, water can flow either into the backwash system or to Ⓗ, the outlet building.

For purposes here, the backwash system can be eliminated since this analysis pertains only to the immediate response period and not to the longer recovery period. The plant can generally operate for one day before backwashing is indispensable. Ⓖ represents the backwash system, which recycles water through a variable filter, Ⓘ, which represents some (unknown or variable) filter being cleaned. From Ⓘ, flows proceed to Ⓙ (the waste washwater tank) from where flows can be valved into Ⓑ (the inlet control building).

Vulnerability

Table 1 lists significant nodes and links used in the analysis here. It contains only essential items for response, although the noted redundancy in the basins, for instance, makes their failure as a whole unlikely. Backup generators, too, have been ignored since the plant can run for some time without power. Plant shutdown may also result from severe damage to basins or other components not because flows are impeded but because prudence would suggest saving the plant from serious long-term losses rather than trying to maintain flows immediately at all costs. Such systematic features of resulting failure are briefly described in Table 1. In addition, a provisional list of special seismic vulnerabilities is provided. Those have not been correlated with different intensities (accelerations, velocities, displacements, durations) of groundshaking.

Even the simplified analysis provided in Table 1 strongly suggests the complexity of the plant operation and how possible secondary problems, such as loss of sand if the underdrains fail, could arise if rapid measures are not taken to shut down the plant for inspection and possible repair.

Table 1 suggests that plant shutdown would be needed given any of the following contingencies:

1. Pipe rupture through the plant, except for limited ruptures in the pipe gallery F

2. Structural failure to any of the following buildings:

   - Inlet control building B
   - Chemical building D
   - Filter building E

3. Rupture of chlorine tanks

4. Low flows from the creek or failure at C, and structural failure of the diversion structure A

5. Severe spalling of the outlet channels

Table 1 further suggests additional reasons why the plant may be shutdown. A full catalogue of structures and equipment may indicate still further contingencies that can lead to shutdown of operations.

Network Reliability

Figure 2 represents a schematic of the water flow system discussed above. The schematic is designed to be used in conjunction with standard reliability techniques. In this regard, special attention is given to recognize those operations that exist in series and in parallel. For those components in series, the reliability factor is given by

$$R = \prod_{i=1}^{n} r_i$$

where r_i is the reliability of component i, and n is the total number of serial components.

For those components in parallel, the reliability function is given by

$$R = 1 - \prod_{i=1}^{n} (1 - r_i)$$

For those cases where k out of n components must function, and the individual reliabilities are equal, the reliability function is given by

$$R = \sum_{i=k}^{n} \binom{n}{i} r^i (1 - r)^{n-i}$$

By representing a system as a network of nodes and links that operate in series and/or parallel, the above expressions can be applied to assess the reliability of a system or set of subsystems. The next section describes how this procedure was applied in assessing the reliability of the subject filtration plant.

EXAMPLE

An example of component reliabilities is presented in Table 2 for a shaking level of Modified Mercalli Intensity VIII. The major components of Figure 2 and Table 1 are listed in Table 2. For purposes here, the backwash system was omitted to simplify the seismic vulnerability analysis of the plant. Also presented in Table 2 are the number of such components, the number (N) that must survive for plant survival, the reliability of individual components at MMI VIII, and the probability that N components will survive at MMI VIII.

The reliability of individual components was taken from seismic vulnerability models described in Reference 1. These vulnerability models typically relate cumulative probability of failure to Modified Mercalli Intensity. The probability of N components surviving was computed using the reliability expressions given in the previous section and which are described in Reference 2.

Based on the reliabilities presented in Table 2, the conditional reliability of the example plant given the occurrence of an MMI VIII event is 0.45 (the risk to the plant given an MMI VIII event is computed as one minus the reliability, or 0.55). The unconditional reliability at this MMI level is computed by adding the product of 0.45 and the occurrence probability of an MMI VIII to the nonoccurrence probability of an MMI VIII. The total reliability, i.e., considering all MM intensities, is computed by repeating the above analysis for all MMI's and then aggregating these results.

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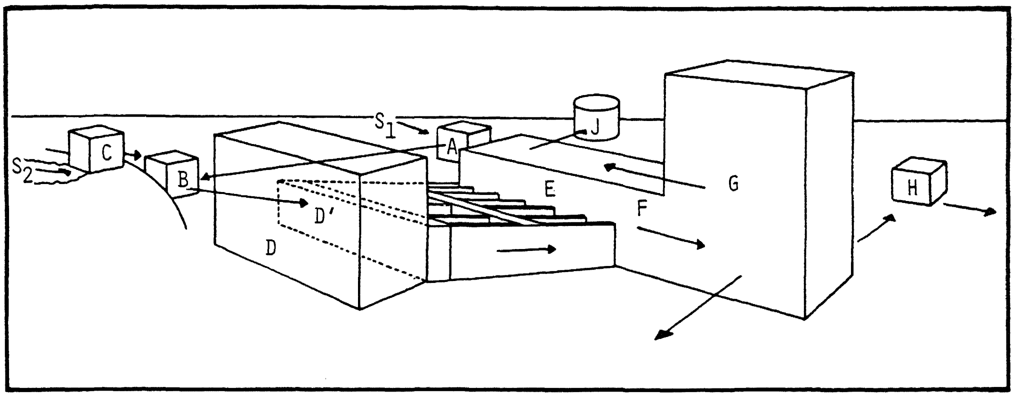

FIGURE 1. PERSPECTIVE RENDERING OF A FILTRATION PLANT

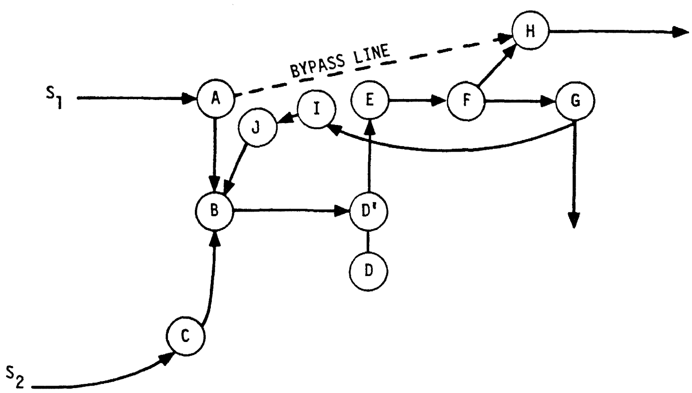

FIGURE 2. FLOW DIAGRAM OF A SELECTED FILTRATION PLANT

CODE: S_1 = MAIN SUPPLY SOURCE

S_2 = VARIABLE SUPPLY SOURCE (CREEK)

A = DIVERSION STRUCTURE

B = INLET CONTROL BUILDING

C = SCREEN HOUSE

D = CHEMICAL BUILDING

D' = CONNECTION BETWEEN AERATION CHANNELS AND MIXING AREA

E = FILTER BUILDING

F = PIPE GALLERY AND POST-CHLORINATION AREA

G = BACKWASH SYSTEM

H = OUTLET BUILDING (FOR FLOWS INTO MAIN TRANSMISSION LINE, OR AQUEDUCT)

I = FILTER BEING BACKWASHED

J = WASTE/WASH WATER TANK

TABLE 1. EXEMPLARY VULNERABILITY TABLE FOR A SELECTED FILTRATION PLANT

Node/ Link	Description	Function(s)	Essential Process Equipment or Structures	Special Seismic Vulnerabilities*	Description of System Features if Failure Occurs
A	Diversion Structure	To divert water to inlet control building or to bypass line	Concrete Building Pipes	SF SH, R, B	Adequate flows would be needed from S_2 (creek).
B	Inlet Control Building	To divert water from either A or C to grit collection and aeration channels	Concrete Building Pipes	SF, (S) SH, R, B	Plant shutdown.
C	Screen House	To screen debris, from S_2 (creek) only	Concrete Building Pipes Power-Driven Equipment	SF, (S) SH, R, B PO	None unless S_1 - A fails (S_2 is a secondary, variable supply source).
B to D'	Grit Collection, Areation of Water	To collect grit and aerate water	Concrete Channels	S (SF – unlikely)	Possible long-term substructure problems if soil is saturated.
D	Chemical Building	To provide sources of chemicals, power, and information	Concrete Building Chlorine Tanks	SF, (S) SL, R	Capacity to chlorinate is essential in the short-run. Other functions have varying degrees of importance. Plant shutdown for failures here.
D' to E	Mixing, and also coagulation and sedimentation basins	To add alums and other chemicals; also mixing, coagulation and sedimentation	Coagulation Basins Sedimentation Basins	S S	Extreme redundancy given number of basins. Possible long-term substructure problems may require closing some basins.
E	Filter Building	To filtrate, chlorinate water	Concrete Building Underdrains (6")	SF, (S) SF	Extreme redundancy, but extensive damage could lead to severe long-term problems.
F	Post-Chlorination	Chlorination outlet	Concrete Building Pipes	SF, (S) SH, R, B	If pipe rupture occurs, such as through structural failure or differential movement, plant operations might be stopped to repair damages.
H	Outlet Building	To transport finished water to main transmission line (aqueduct)	Concrete Channels	S, R	Failure could lead to channel failure.

*Code for special seismic vulnerabilities (those typically that could lead to plant shutdown):

SF = Structural failure or collapse; SH = Shearing at wall or floor; R = Rupture; S = Spalling or cracking; PO = Power outage; SL = Sliding; and B = buckling or bending

TABLE 2. COMPONENT RELIABILITIES AT MMI VIII

Component	No. of Components	No. that Must Survive for Plant Survival, N	Reliability of Individual Components at MMI VIII	Probability that N Components will Survive at MMI VIII
Diversion Structure (A)	1	One or the other	0.85	0.85
Screen House (C)	1		0.85	0.85
Inlet Control Building (B)	1	1	0.85	0.85
Chemical Building (D)	1	1	0.85	0.85
Chlorine Tanks (D) (well-secured)	2	1	0.90	0.99
Sedimentation Basins (DE)	10	2	0.50	0.99
Filter Building (E)	1	1	0.85	0.85
Filter Basins (E)	10	2	0.50	0.99
Pipe Gallery (F)	1	1	0.90	0.90
Outlet Building (H)	1	1	0.85	0.85