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Seismic Design Decision Analysis
Report No. 27

EFFECTS OF EARTHQUAKES ON SYSTEM PERFORMANCE OF WATER LIFELINES

by

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May 1976

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ABSTRACT

Several past earthquakes and their impact on water systems are described, and characteristic damages which resulted are pointed out.

Because of the importance of water lifeline networks after earthquakes, a method for analysing the impact of earthquakes on their system performance is developed. The part of this analysis which deals with ground failure-induced damage to pipes in poor soil is applied to the water system of the Metropolitan District Commission, Commonwealth of Massachusetts. Various levels of pipe damage are simulated, and the impact of these damage levels on system performance is evaluated.

PREFACE

This is the 27th in a series of reports under the general title of Seismic Design Decision Analysis. The overall aim of the research is to develop data and procedures for balancing the increased cost of more resistant construction against the risk of losses during possible future earthquakes. The research has been sponsored by the Earthquake Engineering Program of NSF-RANN under Grant GI-27955. A list of previous reports appears at the end of this report.

This report is identical with a thesis submitted by Klaus H. Hein in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

Dr. Robert V. Whitman, Professor of Civil Engineering, is the principal investigator for the overall research project. Mr. Jonathan Sargent, Senior Civil Engineer in the Water Division of the Metropolitan District Commission, Commonwealth of Massachusetts, contributed to the successful completion of the thesis.

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CHAPTER 1

INTRODUCTION

1.1 Background on System Performance Analysis

Within recent years considerable work has been done to evaluate the risks to engineered facilities stemming from earthquake occurences. One research project, titled "Seismic Design Decision Analysis," has been ongoing at the Massachusetts Institute of Technology since 1971.

Special attention has been given to seismic risk analyses for individual facilities (buildings, powerplants, etc.) and groups of facilities, where each single facility is located at a discrete site (Whitman et al, 1974; Tong, 1975; McMahon, 1976). These risk analyses have been made by coupling two sets of probabilities. Given a specific earthquake occurrence, the first set of probabilities indicates the liklihood of various levels of ground shaking being exceeded at a specified location. The second set of probabilities indicates the liklihood that a facility (or group of facilities) will experience various amounts of damage at a given level of shaking.

It has also become obvious that seismic risk analyses need to be applied to lifelines to assess their vulnerability to damage during earthquake occurences (Whitman et al, 1975; Duke and Moran, 1975). Lifelines are geographically spread networks on which society is dependent. These networks may be categorized into the following major groups: transportation, communication, energy, and water.

Lifeline networks are of special importance after an earthquake, because they may be vitally needed in disaster relief efforts. Yet the earthquake may have damaged the lifelines to an extent where they can no longer be fully utilized in the relief efforts. For example, a water system may be damaged so extensively that not enough water is available for fighting the fires which may have started due to the earthquake.

Each individual network is made up of key facilities, such as power generating plants in electric power systems and pumping stations in water systems, and of the actual linking elements, such as pipes in the water and gas systems and highways or railway tracks in transportation systems. Various components making up important networks are shown in Table 1.1.

An important aspect of lifeline networks is redundancy. The more redundancy exists within a network, the less the damage of a particular system element will affect the system's overall functioning. As an example, if, within a water system, there are two or three alternate routes to convey water to the same community, then damage rendering one of these routes inoperational will not completely cut off all water from that community.

Because of the impact that the breakdown of lifeline networks may have, the performance of these networks after earthquake occurences needs to be analysed. The results of analyses of this kind can provide information on how existing networks may be upgraded to reduce the impact of earthquakes. Analysis results for planned networks, subjected to hypothetical earthquakes, may suggest changes which would reduce the impact of these earthquakes on the system.

Table 1.1

LIFELINE SYSTEMS AND THEIR COMPONENTS

TRANSPORTATION	Highways:	
		underpasses/overpasses
		tunnels
		bridges
		roadways (cuts and fills)
	Public Transportation (subways/streetcars):	
		bridges
		tunnels
		elevated tracks (trestles, etc.)
		stations
	Railways:	
		embankments
		trestles
		bridges
		tunnels
		stations
	Airports:	
		buildings: vital, needed for operation
		: nonvital
		runways/taxiways
	Harbor:	
		docks/quay walls
		unloading pipelines/storage tanks
		cranes
		access roads
COMMUNICATION	Radio and TV:	
		studios
		coaxial cables
		transmission towers
		emergency power facilities
	Telephone:	
		trunk lines
		central and switching stations
		microwave facilities

(continued on next page)

Table 1.1 - continued

ENERGY	Gas:	
		transmission/distribution lines
		gas production plants
		storage (including LNG)
	Electricity:	
		power plants
		substations
		transformers/switching gear
		transmission lines
WATER	Potable:	
		reservoirs
		aqueducts
		deep-rock tunnels
		distribution mains/pipes
		pumping stations
		treatment facilities
		wells
	Sewage:	
		collection system/mains
		treatment plants
		sewer outfalls

1.2 Past Efforts in System Analysis

A methodology has been developed to evaluate the impact on lifeline systems (Panoussis, 1974; Taleb-Agha, 1975a, 1975b). In this methodology the whole network is discretized into elements. A threshold value is assigned to each element, indicating at what level of acceleration or intensity of shaking the element will be rendered inoperational. Each element's threshold value can reflect at what acceleration (or intensity) the element may be damaged by shaking, or it can reflect when soil failure, which would damage the element, might occur. For every given earthquake the acceleration at the site of each element is evaluated by means of an attenuation law. If the computed acceleration exceeds the element's threshhold value, then the element is taken to be inoperational. Surface breaks due to faulting were not considered in this methodology.

Computer programs were written to implement the developed methodology. Input for these programs consisted of seismic activity data for the geographic area under consideration, attenuation formula constants, topographic layout of the network and configuration of its discretized elements, and the elements' threshold values. Computer program output consisted of probabilities indicating the liklihood that certain objectives could be achieved. These objectives state that specified "output nodes" in the network are to be reached from specified "input nodes." Thus, for example, water from a distribution reservoir reaching several communities could be modeled as an objective. The specified "input" and "output nodes" are also part of the computer input data. Probabilities of achieving various objectives are used to evaluate the impact of earthquakes on the network under consideration.

The methodology has the drawback that it greatly simplifies the system behavior of a network. The specified objectives, and their associated probabilities of success (i.e., that the objectives can be achieved), are a rather simple set of statements about a network's level of functioning after an earthquake. A statement about the overall impact of an earthquake on a network is not really made.

1.3 Purpose and Scope

Because of the diversity in the details of the many lifeline networks, only water lifeline systems will here be considered. Similar studies to this one may be carried out for any other kind of lifeline system.

This thesis will first describe several past earthquakes and their impact on water systems. Based on characteristic earthquake damages sustained by water systems, which will become evident from these descriptions, a general methodology for analysing the risk from earthquakes to water systems will be developed. The end results of the risk analyses will be in the form of statements indicating the functioning of the whole water system after an earthquake.

An actual water system will then be described, namely that of the Metropolitan District Commission in the Commonwealth of Massachusetts. Finally, one part of the developed methodology will be applied to this system. This part will deal with the earthquake-related phenomenon which is judged to present the greatest potential of damage to the system.

CHAPTER 2

EARTHQUAKES AND WATER SYSTEM DAMAGE

2.1 Introduction

Damage studies have been made for many earthquakes of the past. Usually these studies focus on damage sustained by buildings, but sometimes the damage to lifeline systems, including the water system, is also described. However, this description of damage to the lifeline systems is often not very indicative of how a particular system as a whole performed after the earthquake. This is due to the fact that only those parts of a system which were damaged by the earthquake are mentioned. At times the descriptions even state how long the system, or parts of it, were inoperable, or what limitations of the system's functioning were caused by the damage. But no mention is made of how much of the system went undamaged. Thus a rather incomplete damage scenario is presented, as it is not obvious what percentage of the whole system was inoperable.

The optimum set of information about the performance of a water system after an earthquake would be as follows. First, information about the geographical layout of the system (including a rough description of soil conditions) and about the system's major features is needed. Major features described should include the mileage of the main distribution pipes (all those, whose diameter exceeds a set minimum), a list of the major pipe materials and an indication of the extent to which each is used, and a listing of the key facilities, their location and their relative importance within the system. Second, a description of the earthquake-caused damage. This should include a description of how the damage was distributed over the system; that is, where it was located in the system's geographical layout. Further, it is desirous to know what caused the damage at the different locations, whether it was due to faulting, shaking, or soil failures. And third, a description of how the system's overall functioning was affected by the sustained damage.

With this kind of information for a set of past earthquakes, one would be able to predict the general behavior of any water system. Given a water system and a hypothetical earthquake (magnitude and location), and looking at the performance of the water systems in past earthquakes, it would be possible to make a qualitative prediction about the extent and location of damage within the system. This prediction could in turn be linked with the knowledge about the extent of damage versus system functioning, and the performance of the system under consideration could be predicted.

2.2 Water System Damage in Past Earthquakes

Though the descriptions of damage to water systems in past earthquakes do not usually give all the information that is desired for the above-mentioned optimum set of information, it is still of value to consider that which is given. By looking at all the various sets of information about the water systems, it may still be possible to make some predictions about the behavior of water systems after future earthquakes.

2.2.1 Managua, Nicaragua Earthquake - December 23, 1972

The earthquake's magnitude was 6.25 on the Richter scale (Meehan et al, 1973), with its epicenter under the city of Managua. Several surface faults ran through the city. Damage to water mains was severe (Ferver, 1973; Marsh and Yanev, 1973). Within two weeks 300 breaks were reported, and by March this number had grown to 700. About 75% of the house connections were estimated broken. By December 30, only 10% of the city had water service.

Due to the many breaks in the mains and partial immobilization of fire-fighting equipment, fire protection in the most heavily damaged area was practically nonexistent and fires were burning out of control for days in the central city. Even one month after the earthquake fire protection for the city was questionable because of water distribution problems.

The water supply for Managua comes from Lake Asososca, a caldera about 6 km west of the center of the city. After the earthquake, access to the Lake Asososca pumping station, which houses four pumps, each with an 8 million gallons per day capacity, was blocked by landslides. Initial repair work at the pumping station was also hampered by leaking chlorine gas. All four pump suctions were blocked by fallen earth, of which two were cleared initially. A 32,400 volt transformer and the electrical supply line had to be repaired. The chlorination equipment was also repaired and back in service on December 24.

Of the four reinforced concrete tanks in the city storage system one was damaged, experiencing differential settlement and subsequently leaking at the floor joint. The newer, welded steel tanks were not damaged, but the older riveted tanks were damaged by buckling in the shell plates. Pipe connections to the steel tanks were damaged, probably due to differential movements between pipes and tanks.

2.2.2 San Fernando, California Earthquake - February 9, 1971

A Richter magnitude of 6.4 was assigned to this earthquake, and its epicenter was in the San Gabriel Mountains, about 11 miles northeast of the Lower Van Norman Reservoir. However, it needs to be pointed out that faults sloped under the epicentral region and broke the surface in the San Fernando area. The earthquake created a zone of discontinuous surface faulting that extended from the Bee Canyon area of the Santa Susanna Mountains (west of the Upper Van Norman Reservoir) roughly eastward, across the Sylmar - San Fernando area, to the Big Tujunga Canyon area north of Sunland (Scott, 1973). The main rupture segment, designated the Sylmar segment, extended eastward from the intersection of Hubbard Street and Glenoaks Boulevard, across Foothill Boulevard, to the Foothill Nursing Home.

Damage to the water system in the San Fernando area was quite severe (Subcommittee on Water and Sewerage Systems, 1973). The City of San Fernando did not have a completed above ground water system until 11 days after the shock (Algermissen et al, 1972).

The water mains in the epicentral region were damaged extensively. Many surface laterals were broken at the feeder lines, and several hydrants were also broken off as a result of ground movement (Iwan, 1971). In approximately 80 square miles in the San Fernando Valley area, the Los Angeles Department of Water and Power (LADWP) and the Los Angeles County Waterworks distribution systems sustained 856 breaks and 557 service leaks.

Damage to the dams and reservoirs was such that water was still available from them. The Upper and Lower Van Norman Reservoirs, both experiencing ground accelerations up to 0.4 g, sustained sizeable damage and almost failed completely. Detailed damage descriptions for these and other reservoirs and dams may be found in the report by the Subcommittee on Water and Sewerage Systems, 1973.

Both of the Los Angeles Owens River Aqueducts were damaged in the area north of the Joseph Jensen Filtration Plant. The Modified Mercalli Intensity in that area was rated as X (Scott, 1973). The First Owens River Aqueduct was carrying water near capacity at the time of the earthquake. It was badly cracked in many places, but operative with minor repairs and back in limited service after two days. The Second Owens River Aqueduct suffered extensive damage, in particular in the Saugus pipeline portion between Terminal Hill and Magazine Canyon. In this steep hillside location pipes buckled and the pipe supports moved. The damage was due to a massive slide movement which was triggered by the earthquake on the north side of Terminal Hill. At the time of the earthquake the Second Aqueduct had been shut down for repairs. The earthquake damage necessitated extensive repairs, and the aqueduct was not back in service until two months after the earthquake.

The Metropolitan Water District of Southern California's (MWD) 500 miles of distribution pipelines and tunnels received relatively little damage. Damage was sustained by the Balboa Inlet Tunnel, by the San Fernando Tunnel, which was under construction, and by the Santa Monica Feeder.

The Balboa Inlet Tunnel (14 feet diameter, approximately one mile long, from the Foothill Feeder to the Joseph Jensen Filtration Plant) was damaged over a length of about 300 feet at a distance of 1500 feet from the downstream portal (Scott, 1973). The tunnel lining was badly spalled and cracked, and some of the reinforcing steel was deformed. The Modified Mercalli Intensity was rated at X for this location. The zone of damage was in an area where the tunnel lies below a canyon. The damage itself was longitudional in relation to the tunnel alignment, and, hence, is not parallel to bedding or nearby fault traces. Because of this evidence, it was believed that the zone of damage was a result of strong ground shaking under local shallow cover (Metropolitan Water District of Southern California, 1973).

The San Fernando Tunnel (18 feet diameter, 29,000 feet long) was at the time of the earthquake two-thirds excavated from its eastern portal. The tunnel is mainly in alluvium and old alluvium, and it experienced a six and one-half foot vertical displacement between its portal and a point four and one-half miles into the tunnel. For the length of the tunnel a Modified Mercalli Intensity of X applied, yet the tunnel was only very slightly damaged, the damage consisting principally of cracking and spalling of a few of the tunnel supports.

The Santa Monica Feeder, a 42-inch diameter concrete pipe with lead-gasketed joints, had two minor pipeline joint separations near Burbank. The Modified Mercalli Intensity in this area was VII.

The LADWP's major distribution facilities were, as already mentioned, damaged considerably in the San Fernando Valley area. Neighborhoods in the Mission Hills, Granada Hills, Porter Ranch, and Sylmar areas were cut off from the water supply. Some of the major distribution elements damaged were the Granada and Susanna Trunk Lines and the Maclay and Chatsworth High Lines.

The Granada Trunk Line, a 49 1/2-inch outside diameter steel pipe with welded slip joints, 4,066 feet long, runs through a utility corridor on the east side of the Joseph Jensen Filtration Plant. The ground in this corridor is 16 feet of engineered fill. The pipeline had 10 failures, most of a compressive nature. Of these ten failures, two were at mechanical couplings and eight at welded slip joints. This damage occured due to a fill slump in the utility corridor (Figure 1, Metropolitan Water District of Southern California, 1973). The Susanna Trunk Line, a 54-inch outside diameter steel pipe with welded slip joints, was considerably damaged north of the Joseph Jensen Filtration Plant. In this area ground ruptures occured, and evidence points to a tectonic origin of these ruptures (Yerkes, 1973). A total of five joint failures occured, one of which was that of a mechanical coupling in a vault.

The Maclay High Line is about 4 1/2 miles long, of which 1 1/2 miles is 6 1/2-foot high tunnel. The remainder is a 5-foot high by 6-foot wide covered concrete conduit. The high line runs from the First Owens River Aqueduct in Magazine Canyon eastward to the Maclay Reservoir (Eldridge Avenue and Astoria Street), crossing through the Olive View Hospital property. It was in an area of Modified Mercalli Intensity X. Part of the area transversed by this high line experienced vertical movements of up to two feet. The Maclay High Line also crossed the Olive View Fault.

It suffered considerable structural damage, requiring three weeks and \$ 148,000 for repairs. The Chatsworth High Line, a 6-foot high by 6 1/2-foot wide concrete conduit about 9.8 miles long, runs from the Van Norman Reservoir to the Chatsworth Reservoir, and thus was is an area ranging in Modified Mercalli Intensity from VII to IX. This high line's design was basically identical to that of the Maclay High Line, but it also incorporated several tunnels and steelpipe siphons. Damage to the Chatsworth High Line was slight, requiring only \$ 4,500 in repairs. This may have been due to the fact that it did not cross areas where ground failures occured, and so damage was solely from earthquake-induced shaking of the structure.

The Joseph Jensen Filtration Plant with its underground reservoir experienced accelerations up to 0.4 g, and it was the only treatment facility to receive major damage. At the time of the earthquake this facility was still under construction, though near completion. In the underground water reservoir there was failure of the roof diaphragm, failure of walls in bending, and damage to the support columns. These damages were mainly from the severe shaking of wet foundation materials. Parts of the filtration plant, such as the chemical building, were also heavily damaged because of settlement and sliding of the engineered fill on which the facility had been built. The base of sliding probably occured along a liquefied layer caused by the seismic shaking of the subsoils (Metropolitan Water District of Southern California, 1973). It can be seen that, had the filtration plant been operational, the earthquake would have greatly reduced its functioning, if not rendered it completely inoperational.

Further descriptions of the performance of storage facilities, as well as for that of wells, are given in the report by the Subcommittee on Water and Sewerage Systems, 1973.

Water mains in the minor distribution facilities also experienced various kinds of damage. For uncoated steel mains the most prevalent damage was in the form of internal water pressure punching holes in the wall of pipes where these had been weakened by corrosion. Damage to cast iron pipes was most often in the form of circumferential cracks resulting from earth movement. With more pronounced earth movement some of the cast iron mains shattered. The greatest number of joint failures in cast iron mains was where cement-caulked joints were used, though a number of lead-caulked joints failed as well. Horizontal and vertical ground movements would loosen the caulking, which was then blown out of the joint by the water pressure. Most frequently horizontal ground movements would cause joint failure in caulked and welded pipes by pulling the joint apart.

2.2.3 Santa Rosa, California Earthquakes - October 1, 1969

Two earthquakes occured on the same day, spaced about one and one-half hours apart. The epicenters of both earthquakes were very near the city of Santa Rosa. A Richter magnitude of 5.6 was assigned to the first earthquake, and a magnitude of 5.7 to the second (Steinbrugge et al, 1970). Within the city the Modified Mercalli Intensity was rated as VII to VIII.

A total of 22 pipe failures were tabulated for the city of Santa Rosa. Repair work on the water system was started about 5 hours after the second shock, and all mains had been repaired 12 hours later. Damage to the system's water pipes was such, that repairs, with one exception, did not require placing more than one fire hydrant out of service during actual repair work.

Damage to steel water mains was usually in the form of small holes. Most likely these holes were caused by water pressure surges, which would puncture the pipe walls at locations weakened by rust. Some other modes of damage were compression failures due to horizontal movements in structurally weak alluviums, failures due to differential horizontal ground motions, and failures at locations of differential vertical compaction (e.g., where pipes cross from firm soil into softer soil).

2.2.4 Helena, Monatana Earthquakes - October 12 and 18, 1935

The earthquake of October 12 had a Richter magnitude of 5.7, and its epicenter was close to the city of Helena (Blume, 1973). The only reported damage to the Helena water system was to a 4-inch cast iron line serving the County Hospital (Lupien, 1936). The total length of the pipe was 6,000 feet, of which approximately 1,000 feet were laid in a swamp. The joints of this pipe were precaulked with lead, and the pipe was not anchored in any way to keep it from shifting. In the section which was laid in the swamp 12 loose joints were found. Earthquake motion, made more severe by the nature of the ground in the swamp, probably caused large movement of the pipe, loosening the lead caulking of joints.

A Richter magnitude of 6.3 was assigned to the first earthquake of October 18. The Woolston pump house, a brick structure, was badly cracked. To save the pump in case of another shock an 18 foot by 15 foot by 10 foot casing, made of 8-inch by 6-inch timbers and 3-inch planks, was built around the pump.

The second shock of October 18, with a magnitude of 6.3 and an epicenter close to the city, lead to the collapse of the pump house. The pump, however, was saved and operational due to the casing around it. None of the treatment facilities, neither buildings nor equipment, suffered damage from the earthquakes. All of the buildings were brick structures with wood roofs, except for one building which had been dug into a steep hillside and had a reinforced concrete roof with a light earth cover.

As a result of the two October 18 earthquakes the County Hospital pipe had 30 more loose joints in the swamp. These were again tightened by driving the lead back into the joint. The only other damage due to these two earthquakes was to an 8-inch vitrified tile flow line, which was badly cracked over a length of about 15,000 feet and had to be replaced.

2.2.5 Long Beach, California Earthquake - March 10, 1933

The Long Beach earthquake had a Richter magnitude of 6.3 (Wiggins and Moran, 1971) and its epicenter was about 15 miles from the city of Long Beach.

The earthquake caused minor or no damage to steel tanks and cisterns, booster pump foundations, pumps, pipe connections to pumps or to electrical switches (Porter, 1934). The power line to one pumping plant was broken, rendering it inoperational for 8 hours. Also a portion of a brick wall fell at another pumping plant causing damage to a transformer, which required two and one half hours for repairs.

No damage was done to the pumping and electrical equipment or to pipe connections at the wells. However, movement at each of the well locations was indicated by the shifting of heavy transformers on their foundations and by cracks in the concrete floors of the pump houses.

The greatest damage was done to the pipe network. The reinforced concrete collection mains, ranging from 16 to 42 inches in size and having a total length of 6.8 miles, conveyed water from water-bearing land northeast of the city to the booster plants. The soil in which they were laid is naturally deposited silt (sic), the ground water level being well below the bottom of the trench at the time of construction. Some failures occured to these pipes, none of which required any mains to be put out of service immediately after the earthquake, so that they were used for two to eight days before being shut down. All these failures, except one, resulted from a lack of flexibility between the pipes and fixed structures.

The distribution pipes consisted of cast iron and steel pipes. There were 367.5 miles of cast iron pipes, ranging in size from 2 to 30 inches. A total of 130 breaks occured in the cast iron pipes, of which only one break was in a pipe with a diameter greater than 12 inches. Of these breaks 52% occured in the southeastern part of the city where land has been built up by a dredged fill on tide flats, 38% occured where the soil is a naturally deposited silt (sic) with groundwater near the surface, and 10% in hard adobe soil. Though 90% of the failures occured in poor soil, no evidence of liquefaction was observed during this earthquake.

Steel pipes, 2 to 16 inches in size and having a total length of 21.8 miles, incurred 135 breaks. All of these breaks were in one district of the water system where the pipes had reached a condition where replacement was already necessary. Based on this description, it is probable that rust had created thin spots in the walls of the pipe, which led to failures due to "blowouts" during the earthquake.

Out of 10,454 cast iron service laterals 85 failed, 10 failure occurring in the silty (sic) soil in northern Long Beach and 75 in the dredge-filled tide flats in the Belmont Shore - Naples area.

2.2.6 San Francisco, California Earthquake - April 18, 1906

April 18, 1906 is perhaps more often remembered as the day on which the San Francisco fire started, but it was the earthquake of that day which led to the start of the fire and which damaged the water system to such a degree that fire fighting was almost impossible. The ensuing conflagration lasted for three days.

Information may be found on the assessment of the conflagration hazard previous to the earthquake ("Water Supply, Fire Protection...," Engineering News, 1906), on all the damage due to earthquake and fire ("The San Francisco Disaster...," Engineering News, 1906; Derleth, 1907; Lawson, 1908), and on steps that were taken after the earthquake of 1906 to ensure an adequate water supply for fire fighting in the future (Eckart, 1937; "Fire Protection for San Francisco," Municipal Journal and Engineer, 1909; National Board of Fire Underwriters, 1939). Here only the earthquake damage to the water system will be described (Committees of the San Francisco Association of Members of the American Society of Civil Engineers, 1907).

The Richter magnitude of the earthquake was 8.3, and its epicenter was put at $38^{O}N$, $123^{O}W$ (Coffman and von Hake, 1973), which is approximately 35 miles from downtown San Francisco. The earthquake caused large movements along the San Andreas fault.

The two Crystal Spring dams (the older earth dam separating the lake into two parts, and the newer concrete dam also known as San Mateo dam), the San Andreas earth dam, and the Pilarcitos earth dam all performed well during the earthquake and continued to serve their function. The Crystal Spring earth dam and the San Andreas dam were both on the direct fault line.

On the peninsula, in connection with the San Francisco Water Works, there were six important pumping stations (refer to Figure 2.1 for their location and for the following description). Two of these were within the built-up sections of San Francisco, one being in a brick building and having a brick stack and the other being in an old, partly brick, partly corrugated iron building and also having a brick stack. The other four pumping stations were at Lake Merced, at Milbrae, at Belmont, and near the San Mateo Dam. These four were all housed in buildings of corrugated iron construction supported on timber frames, and they had individual, guyed steel stacks. None of the six pumping stations suffered any material damage affecting their serviceability. This was probably due to their foundations being sufficiently massive to cause important units to move as a whole.

On the eastern side of the San Francisco Bay there was one important pumping station, supplying about one-third of the water for the cities on that side. It was situated on marsh land, about one mile west of Alvarado. The building, engines, and boilers were supported on pile and concrete

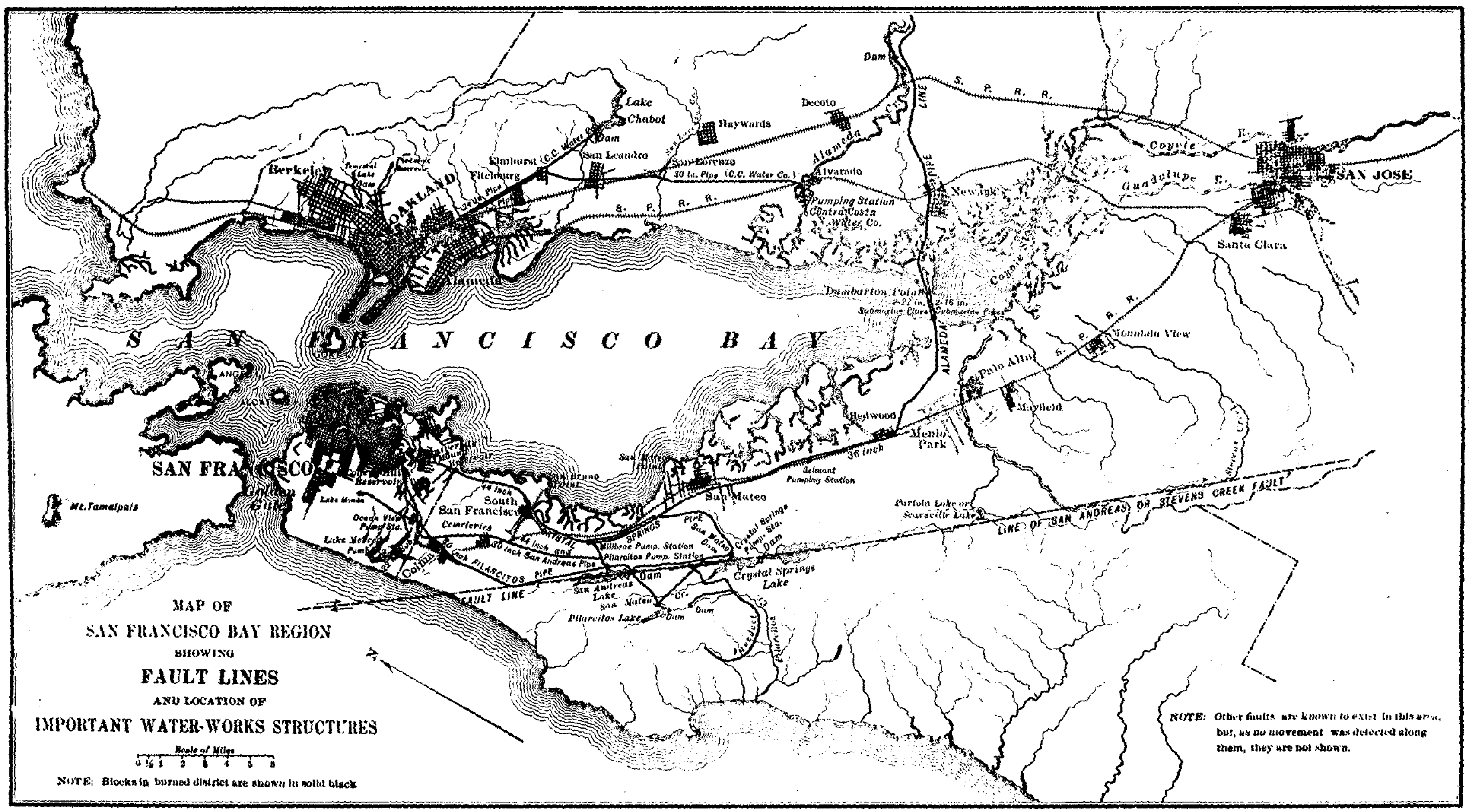

Figure 2.1 - Water-Works Structures of the San Francisco Bay Region in 1906 (Committees of the San Francisco Association of Members of the American Society of Civil Engineers, 1907)

foundations, and individual, guyed steel stacks were used. Although the brick wall of a part of the building was so badly damaged as to require reconstruction and the fuel tank was heavily damaged, the machinery equipment was not damaged.

The pipe lines within the water system supplying San Francisco were the part so damaged as to bring about the breakdown of the system. No considerable damage was caused to pipes which had been laid in firm ground. All the important failures to pipes occured where they were supported above the ground on wooden trestles, where they were intersected by the fault line, and where the earthquake shock produced serious unequal ground settlement.

Three long, riveted-iron pipe lines led from the storage reservoirs into San Francisco. Damage to them was severe. For two weeks no water from the Pilarcitos, Crystal Springs, or Alameda sources could be conveyed to San Francisco. Only the San Andreas pipe remained operational, so that San Andreas Lake for some time was the distributing reservoir for the city. The San Andreas pipe line, a 36-inch pipe, was fractured at only one point. This was at Baden (west of South San Francisco), where the pipe crossed an area of marsh land on a wooden trestle. A slip joint had been provided at this point, the amount of movement being restricted by four bolts attached to lugs which were riveted to the pipe on each side of the joint. Excessive movement of pipe and trestle, probably brought about by the behavior of the marshy ground during the earthquake, caused the 1/4-inch sheet to which the lugs were attached to be torn out.

The Crystal Springs pipe line, a 44-inch laminated wrought iron pipe with 1/4-inch wall thickness, sustained damage at three locations. Two of these were minor, but the third was the most extensive damage done to any of the pipe lines, except for the damage to the Pilarcitos pipe near the fault. This serious damage occured where, for a length of about 2,000 feet, the pipe crosses the San Bruno marsh. The pipe was supported on trestle bents resting on pile foundations, and the piles penetrated the mud, on the average, to a depth of 40 feet. The main failure modes were breaks at transverse riveted joints, due to tension and crushing, and complete dislocation of the pipe, such that it was entirely thrown off the supports on either side. Both of the failure modes were apparently due to the behavior of the ground in the swamp during the earthquake. If the movement of the ground caused the tops of adjacent piles to tilt away, or toward, each other, this would create tension or compression in the pipes. Pipes were most likely thrown off their supports because the piles and trestles would move more violently than the pipe, since the pipe, filled with water, remained relatively stationary due to its inertia.

The Pilarcitos pipe line, from the Pilarcitos Reservoir to Lake Honda, was made up mainly of 30-inch riveted iron pipe, but contained a small part of 24-inch cast iron and 20-inch riveted iron pipe. The center line of the pipe was usually 3 or 4 feet beneath ground surface. For about six miles this pipe line was located along the San Andreas fault, often crossing and recrossing the fault line. The permanent longitudional movement along the fault was generally 6 to 7 feet. Wherever the pipe crossed the fault line, whether buried or supported on trestles, it was badly shattered, the direction of the fault crossing determining whether the pipe was torn apart or telescoped. All ruptures occured at transverse riveted joints, and the tensile breaks and telescoping ranged up to 6 feet. The pipe collapsed at some locations, in one case for a length of 50 feet. At Frawley Gulch, 1/4 mile east of the fault, the pipe was supported by a 100-foot long timber trestle. This trestle collapsed completely. All this damage was so extensive that the Pilarcitos pipe line had to be abandoned.

Damage to water pipes within the city of San Francisco was also very extensive. Even if the three main conduits supplying the city had survived, there would have been great difficulty in fighting the fire, since within the city boundaries many main branch pipes, and the gridiron system in general, were largely destroyed.

All serious damage to water mains was due to lateral displacements or subsidence of filled or soft ground. In the ensuing fire, the explosions of gas mains added further ruptures to the streets and the pipes beneath them. Eckart quotes from a report by Schussler, which gives a description of the damage to the water-pipe system in San Francisco:

"The city pipe distributing system was broken and in many instances torn and twisted off, especially in places where the ground, over which the streets had been constructed, had been poorly and loosely filled over old deep swamps and soft marshes. There were also a number of breaks in the streets that passed with deep loose fills over former ravines.

"In solid ground there was very little trouble and but very few breaks. A number of the breaks noted...as being on solid ground were caused by the use of dynamite and other explosives, employed in blowing down buildings.

"In the above sunken streets the city sewers, as well as other conduits, such as gas pipes, electric light conduits, etc., suffered the same as the water pipes, in that they were also similarly ruptured by the sinking and violent oscillations of the ground.

"On July 18 there had been discovered and repaired 300 breaks in the street pipe system, of which number 276 were in and immediately adjoining the burnt district, while in the entire balance of the city, viz., in the unburnt district, only 24 breaks have been found and repaired.

"But the most serious problem that we have had to meet in rehabilitating the city distributing system has been the work of shutting off the thousands of broken service pipes and house supply pipes...

"The total number of the house, hotel, elevator, standpipe and factory connections and of automatic sprinkler pipes, thus torn off and left open by and during the entire conflagration, amounts to over 23,200 separate pipes in the burnt district. The breaking, tearing and twisting off of the main street pipes in over three hundred places and the openings of these many thousands of service pipes left but little pressure in the main pipes in the unburnt district and for the Fire Department along the burning margin of the same."

Figure 2.2 shows a geologic map of the City of San Francisco. Intensities of earthquake shaking are shown in Figure 2.3. It is readily apparent that the greatest intensities were experienced by areas of man-made land which had previously been marshes and tidal flats. Within these areas ground failures occured, which may have been due to liquefaction.

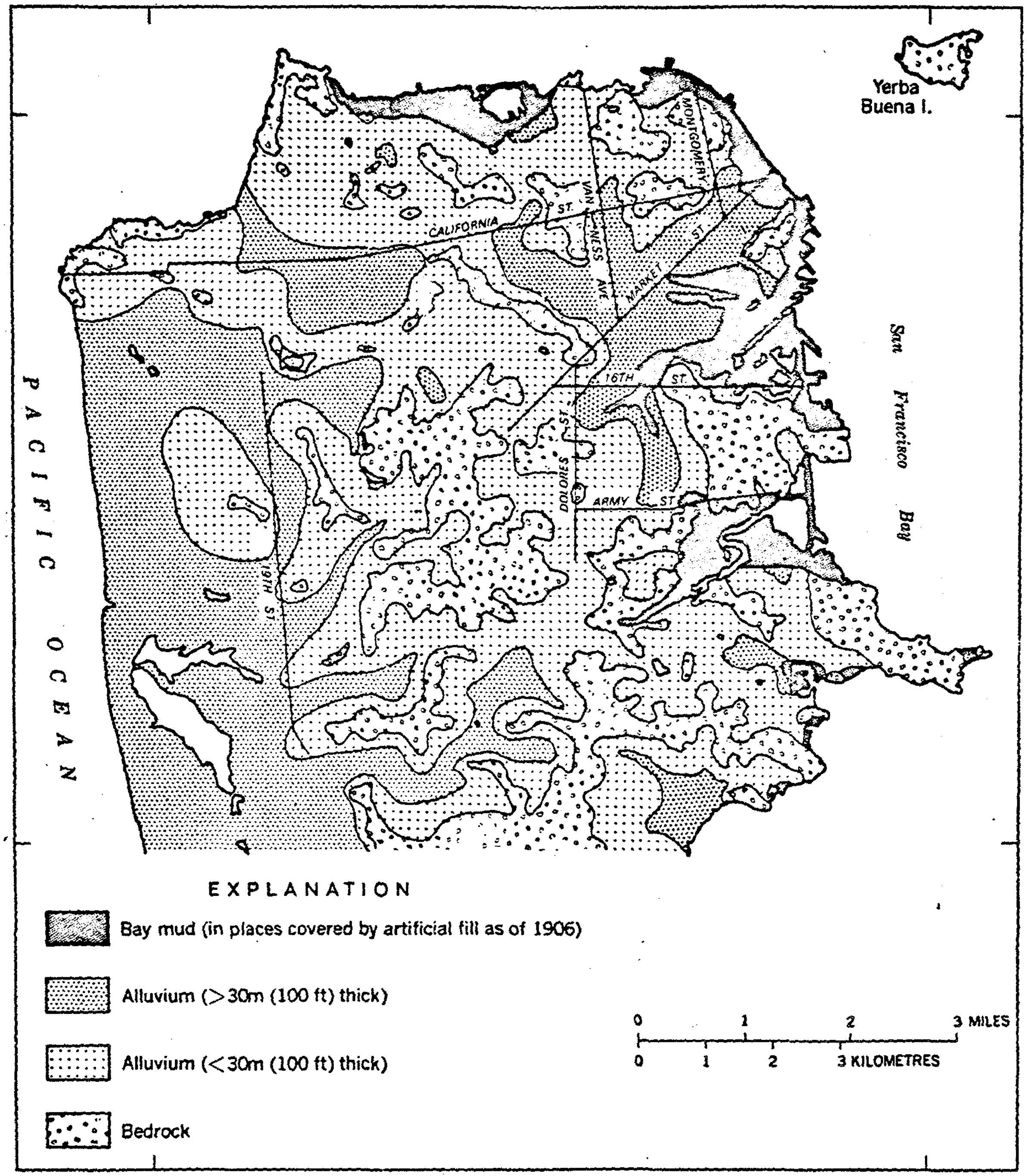

Figure 2.2 - General Geologic Map of San Francisco, California (Borcherdt, 1975)

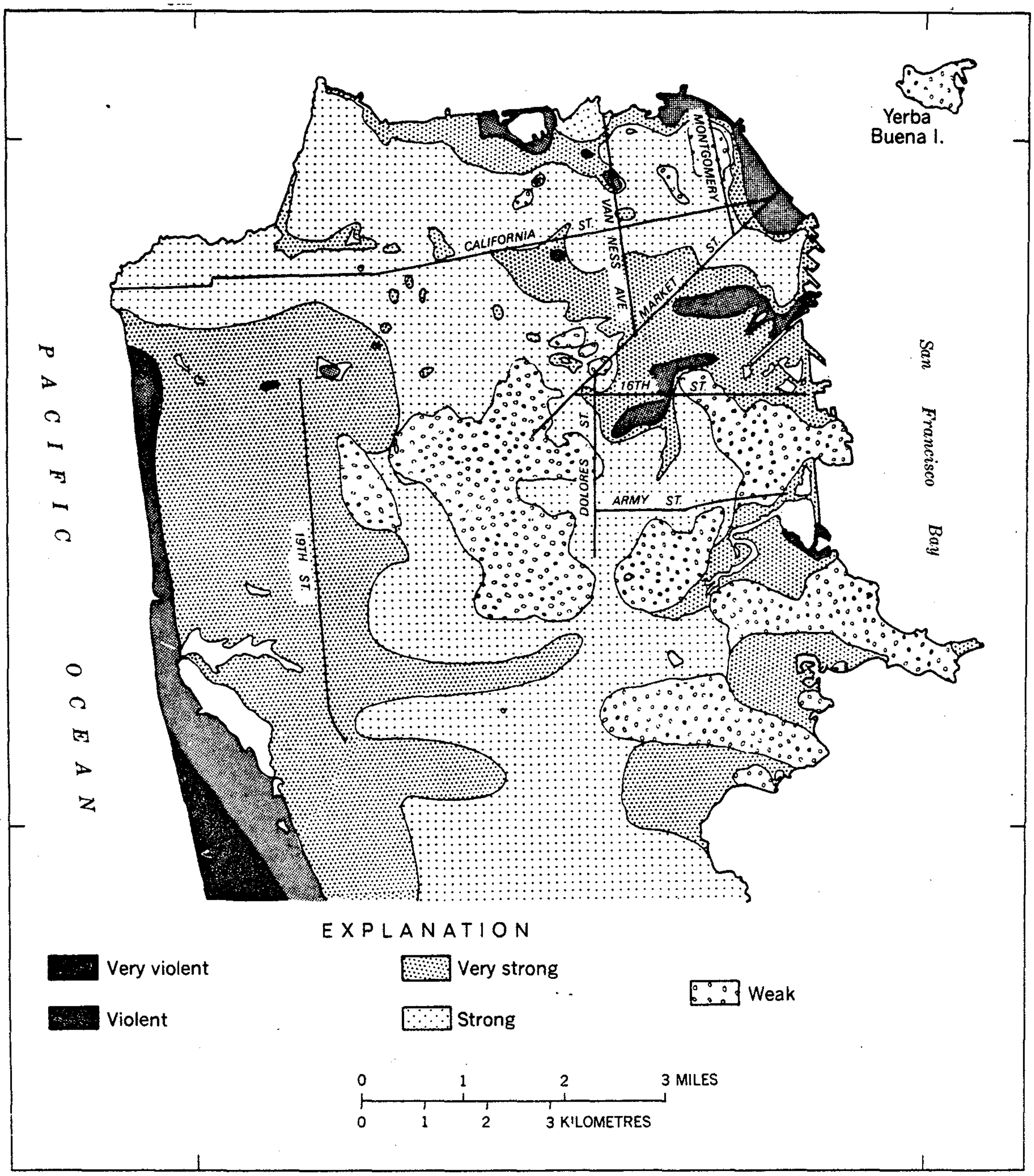

Figure 2.3 - Distribution of Apparent Intensity of the 1906 Earthquake in San Francisco, California (Borcherdt, 1975)

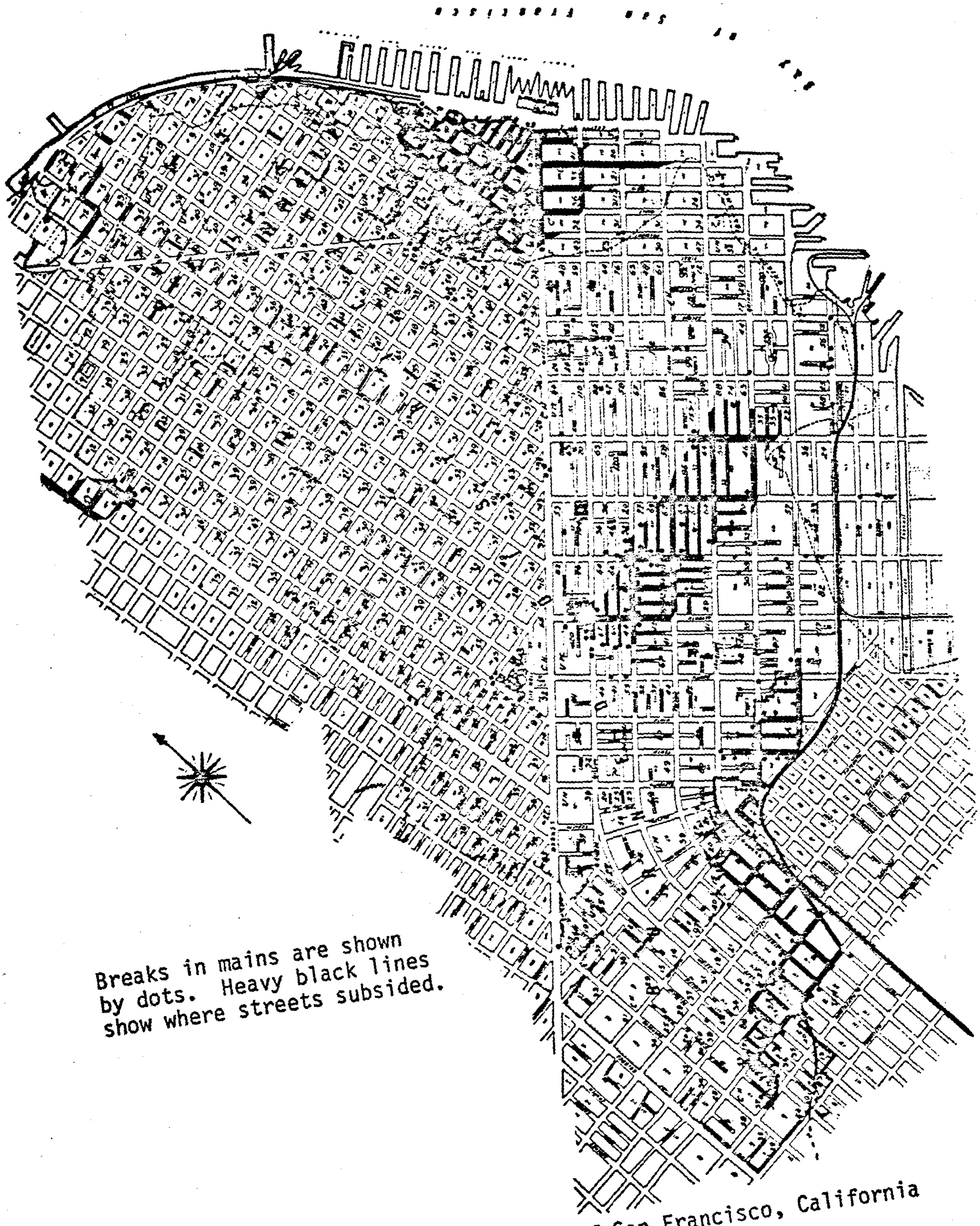

Figure 2.4 - Burnt District of San Francisco, California (Eckart, 1937)

As already noted, pipe damage was heaviest in the burnt district, particularly in the areas of poor soil. Figure 2.4 shows where streets subsided, resulting in pipe failures, and where individual pipe breaks occured in the burnt district. Comparing Figures 2.2, 2.3, and 2.4 the correspondence between poor soil, intensity of shaking, and resulting damage may be seen.

A few of the pipe lines of the Contra Costa Water Company, supplying cities on the eastern side of the bay, were ruptured. All these failures occured in marshy or low-lying alluvial soil.

2.3 Conclusions

The above damage descriptions show that the functioning of a water system after an earthquake is usually determined by the damage to the pipe network. Damage to the pipes is most likely to occur, and is most severe, if one of the following conditions exists.

If the character of the soil in which the pipe is embedded is such that it will displace violently during an earthquake, then extensive damage is likely. The same is true for pipes supported by structures whose foundations are in such soil. Marshes, man-made fills, and soft alluvial soil, all the soils in which liquefaction or excessive settlement may readily occur, fall into this category of "poor" soil, Furthermore, if pipes and their supporting structures are not designed to behave as a unit, allowing all the while for sufficient movement of this whole unit, then differential movement between the two may lead to damage.

Any pipe intersected by a fault line, or in close proximity to one, is liable to be rendered inoperational during an earthquake. Only if the design of the pipe line provides great capacity for movement may the danger of damage be somewhat reduced.

CHAPTER 3

GENERAL METHODOLOGY FOR THE RISK ANALYSIS OF WATER SYSTEMS

3.1 Introduction to Analysis Frameworks

In order to evaluate the effect that earthquakes will have on a water system it is necessary to establish a framework which will serve as an analytical tool.

The initial step within any framework of this kind is the establishment of a set of possible earthquake events for the region considered, specifying magnitude and location for each event. Probabilities of occurence for each of these events may be derived.

3.1.1 Ultimate Refined Analysis Framework

A very refined and completely quantitative analysis framework could be similar to the one shown in Figure 3.1. Each earthquake in the set of likely earthquakes would be considered in turn. The direct earthquake effects may be broken into major categories, such as faulting, shaking, and ground failures. These direct effects may occur individually or in combinations, and to each possible mode of their occurence a probability may be assigned. One such effect mode, occuring in an area of poor soil, might be that of ground failure (i.e.: subsidence, liquefaction). Another mode, occuring in an area where bedrock is close to the ground surface and which is crossed by a fault, might be that of fault breaks combined with severe shaking. The probability for each effect mode, $P[\text{effect } k \mid EQ_n]$,

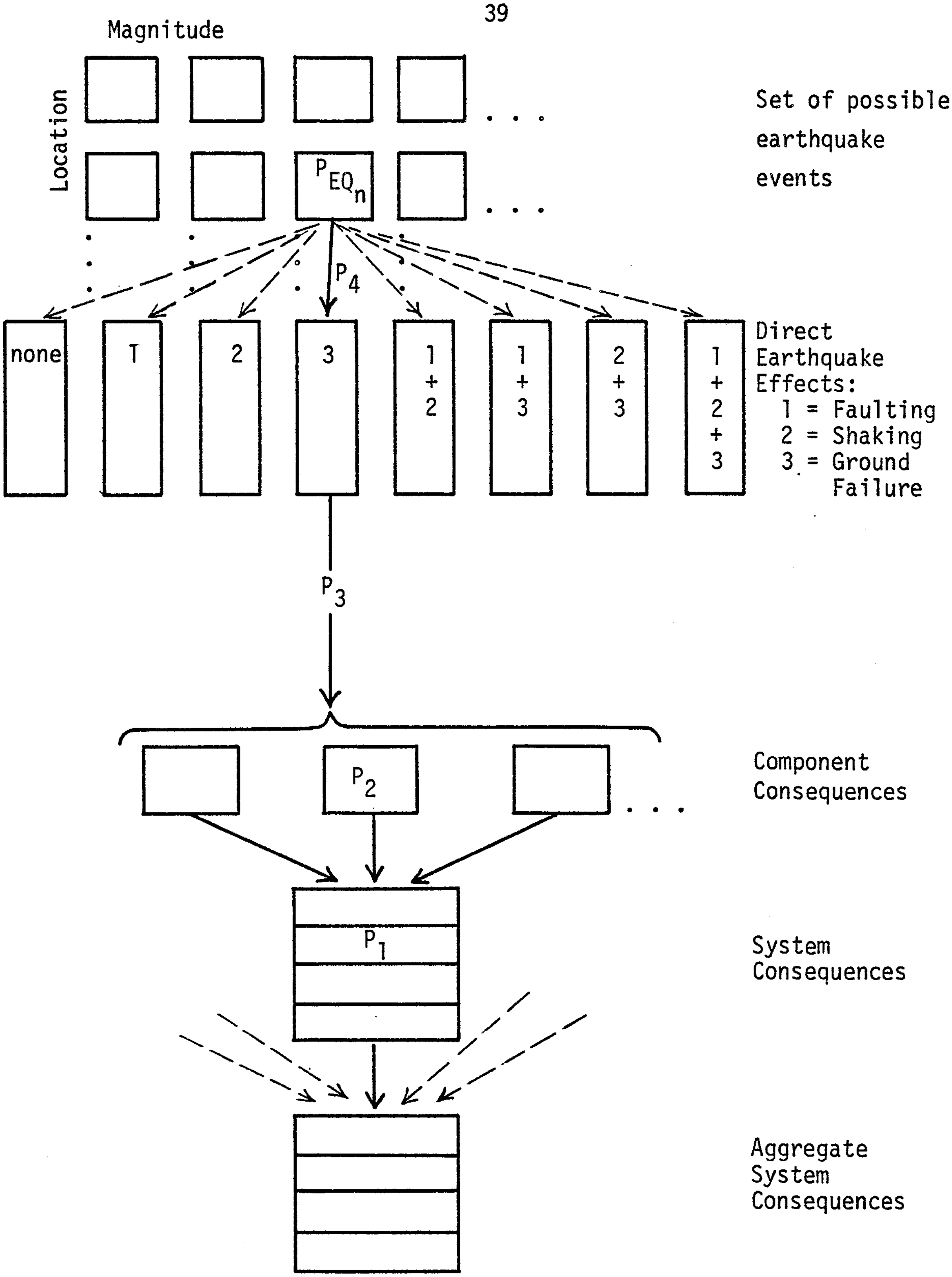

Figure 3.1 - Ultimate Refined Analysis Framework

is the probability that mode k of the earthquake effects will occur, given that earthquake EQ_n has occured. It should be noted that, considering all modes, $\sum_{\text{all } k} P[\text{effect } k \mid EQ_n] = 1$.

For each earthquake effect mode there may exist various degrees of severity. For example, if ground failure (subsidence, liquefaction, etc.) has occured, it may affect only a small portion of the poor soil, say 5% of it, or it may affect a large portion thereof, say 50% or more. As another example, if faulting (surface rupture) occured, it may be limited, say ground movement along the fault for only a few miles, with a maximum displacement of a few inches. Or it may be extensive, for a length of over 100 miles, with displacements of several feet. A probability may be assigned to each degree of severity. This probability, $P[\text{severity } i_k \mid \text{eff } k, EQ_n]$, is the probability of severity state i, given that earthquake effect mode k and earthquake EQ_n have occured. Severity states vary from one effect mode to another, thus the double index in severity i_k.

The next step in the analysis framework is the determination of actual damage done to system components. These damages are here called component consequences and will be further discussed in section 3.2. Given a certain severity state of an earthquake effect mode, probabilities may be assigned to each of the various component consequences. These probabilities are designated $P[\text{comp } j \mid \text{severity } i_k]$, where severity i_k refers to the severity state i within the earthquake effect mode k.

Subsequent to the determination of component consequences, at transition must be made from these to system consequences. System consequences describe the levels of operation that a water system is still capable of when various amounts of its components have been damaged. System consequences are discussed further in section 3.3. In the transition to system consequences a set of probabilities may be obtained, P[sys x | comp j], which are read as probability of system consequence x, given component consequence j.

In the final step the aggregate, or overall, system consequences are evaluated. These aggregate system consequences may be obtained for a particular earthquake EQ_n by summing over all direct earthquake effect modes, all severity levels, and all component consequences. This may be expressed as: P[aggregate system consequence x | EQ_n] =

$$\sum_{\text{all } k} \sum_{\text{all } i} \sum_{\text{all } j} P_1 * P_2 * P_3 * P_4$$

where P_1 = P[system consequence x | comp j]

P_2 = P[comp j | severity i_k]

P_3 = P[severity i_k | EQ_n] and

P_4 = P[eff k | EQ_n].

The aggregate system consequences for all possible earthquakes may also be found, as is shown by

P[aggregate system consequence x] =

$$\sum_{\text{all } n} \text{P[aggregate system consequence x} \mid EQ_n] * P_{EQ_n} .$$

3.1.2 Initial Simplified Analysis Framework

As may be seen from the description of the refined analysis framework in section 3.1.1, a level of sophistication is required which may not be available in the first analysis of a water system. An alternate, more

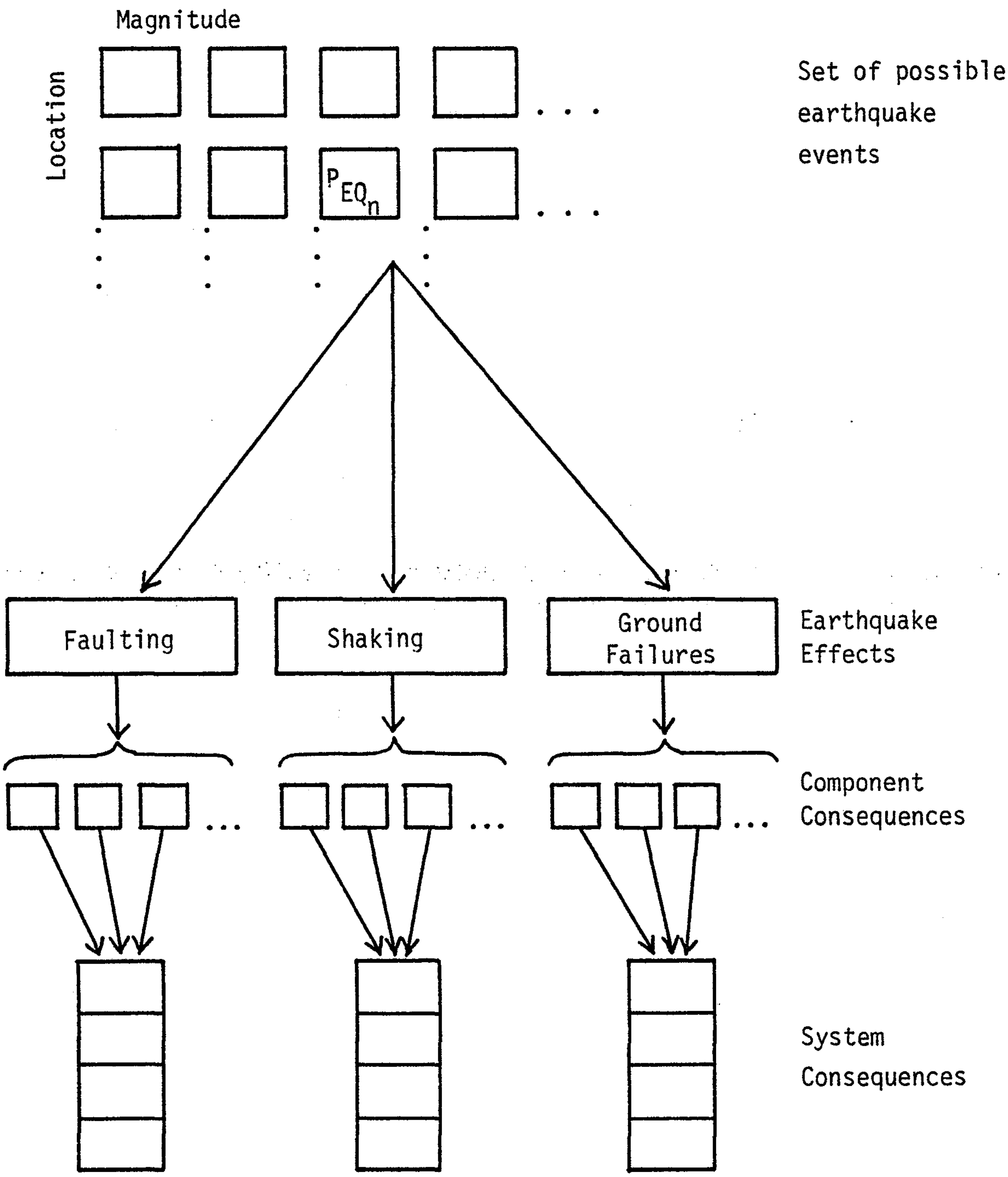

Figure 3.2 - Initial Simplified Analysis Framework

simplified, analysis framework, in which some of the steps are carried out in a more qualitative manner, may be more appropriate. Such a framework is shown in Figure 3.2.

For each earthquake considered, only the three direct earthquake effects by themselves are considered. Again levels of severity within each earthquake effect will be included. The final result is three sets of system consequences, each stemming from one of the direct earthquake effects. No quantitative means of combining these three sets into probabilities of aggregate system consequences is possible. However, the three sets in themselves are of value, and their use will be described in section 3.3.

The remainder of this chapter will deal with the various aspects of the simplified analysis framework.

3.2 Direct Earthquake Effects and Component Consequences for a Given Earthquake

For each earthquake event chosen, the different earthquake effects and the subsequent component consequences must be examined. A possible methodology for doing this will here be described. However, a complete application of this methodology will not be attempted further on in this thesis because of its large scope. Rather, only one facet, that of ground failures and it consequences, will be dealt with.

The term "component consequence" is used to indicate the damage to a water system; that is, it describes which of the water system's elements have been damaged and are no longer operational within the system. Damage to a system is actually a continuous spectrum, ranging from no damage to

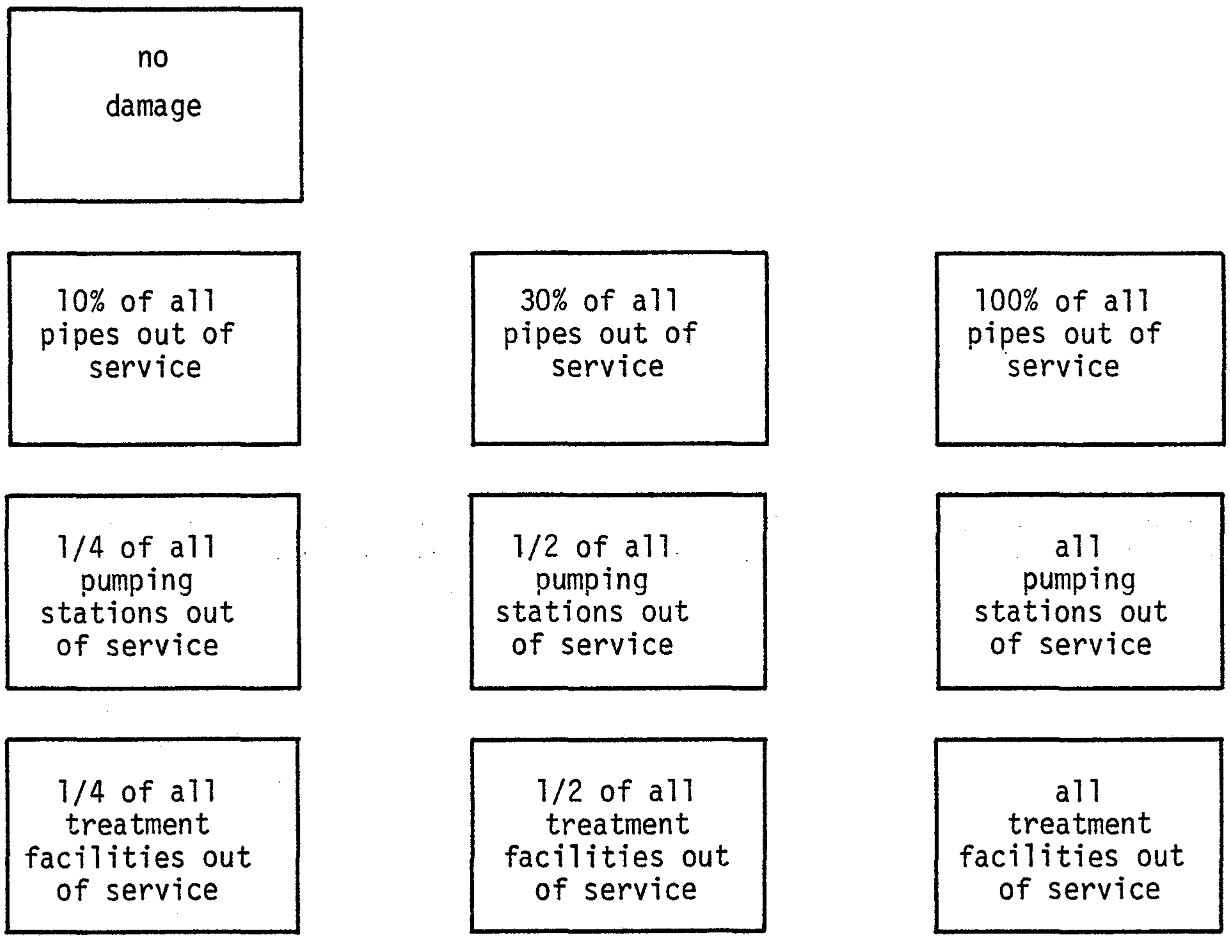

Figure 3.3 - Limited Set of Component Consequences

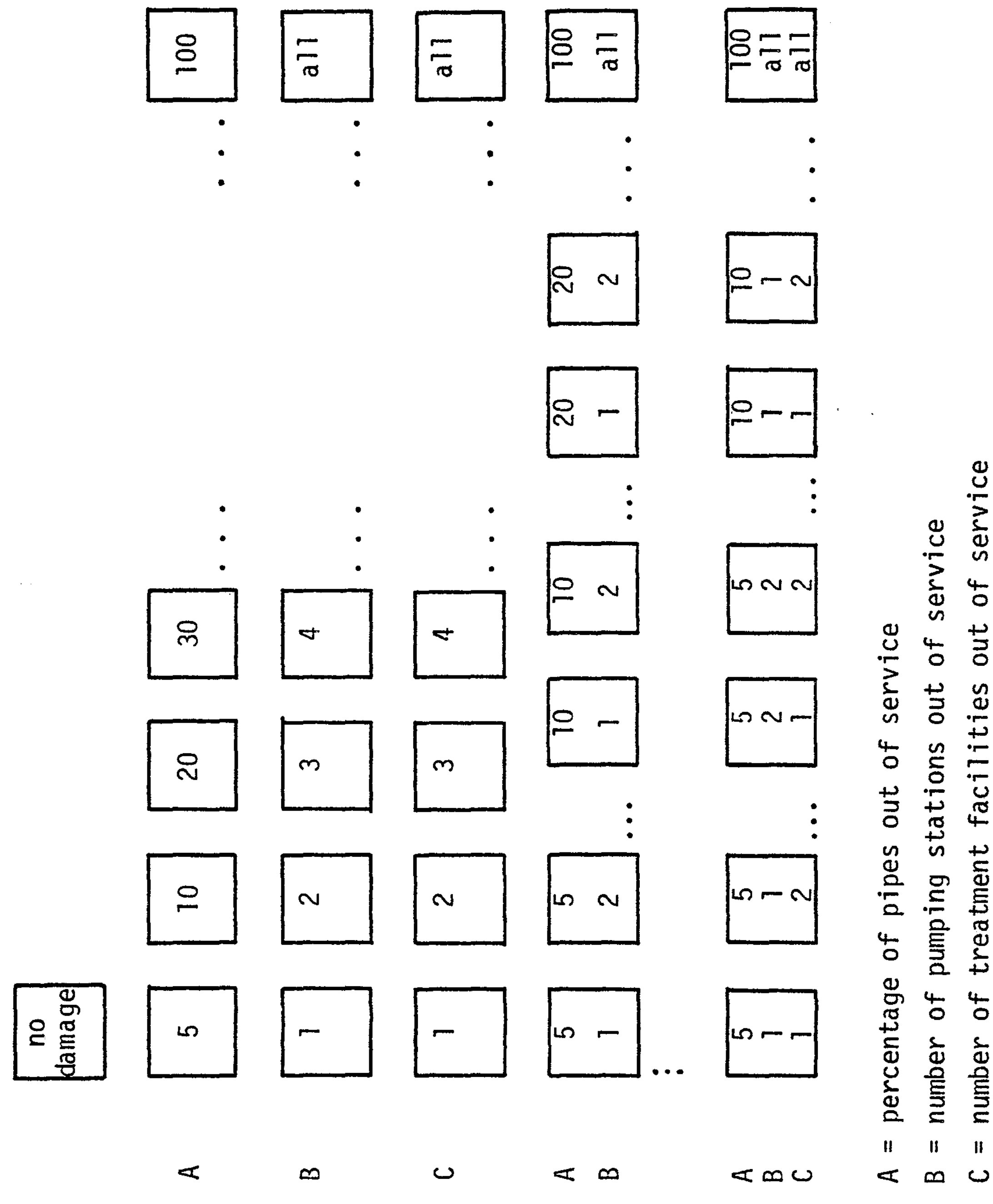

Figure 3.4 - Extended Set of Component Consequences

total damage (when every element is inoperational). For the purposes of analysis we have to break this continuous spectrum into a finite set of component consequences (damage states). For a first analysis this set of component consequences might be rather limited, as shown in Figure 3.3. As the analysis becomes more refined it may desirous to increase the number of component consequences (see Figure 3.4) in order to more closely approximate the actual continuous spectrum of damage.

Given a specific earthquake magnitude and location, and dealing with one of the direct earthquake effects, a probability of occurence will be derived for each individual component consequence in the set being used.

3.2.1 Direct Faulting

Depending on the geology of a geographic region, direct faulting may or may not be a result of an earthquke. If direct faulting is likely to occur, then this may pose a major threat to a water system in this area. For example, in the 1906 San Francisco earthquake direct faulting destroyed the Pilarcitos pipe line, in the 1971 San Fernando earthquake much damage was due to direct faulting, and in the 1972 Managua earthquake direct faulting destroyed many of the supply arteries leading to the eastern part of that city.

Any key facilities of a water system located on a historically known fault are in danger of being rendered partially or completely inoperational in the event of an earthquake. The same danger exists for pipes which cross a fault. Key facilities and pipes in close proximity to a fault would be subjected to severe shaking, which is the direct earthquake effect considered next, in section 3.2.2.

The greatest danger from faulting would be to systems in which a fault crosses all the distribution mains going from one part of the system to another, as was the case in Managua. For a system thus located, movement along the fault might completely cut off all water supplies to part, or possible the whole, of the distribution system. A further example of a water system in which main distribution arteries are intersected by a fault line is that which supplies the Oakland, California area. The Mokelumne Aqueduct, which supplies close to 100% of the water used in this area (Durfor and Becker, 1964), conveys water from the Mokelumne River to four reservoirs on the east side of the Hayward Fault. All four aqueducts coming from these reservoirs into the water distribution system cross the Hayward Fault (Algermissen et al, 1972), and large movements along this fault might thus seriously jeopardize the total flow of water into the Oakland area.

For a geographic area under consideration, given an earthquake magnitude and location, it may be possible to determine the probabilities of surface ruptures or movement along a know fault occuring. These probabilities can express the actual amount of ground displacement which is likely to occur. If an analytical and quantitative method is not applicable, it may be possible to at least obtain some rough probabilities for ground displacement based on past earthquakes in the area under study.

Once the various levels of ground displacement and the associated probabilities of occurence are known, it is possible to evaluate the probabilities of the various component consequences being considered, by determining which components of the water system are on the fault and how they may be damaged.

3.2.2 Shaking

The degree of shaking at a location may be indicated in one of two ways. A number on an intensity scale, such as the Modified Mercalli Intensity scale, may give a general, qualitative indication of the strength of shaking in an area. On the other hand, an acceleration would be a more exact, quantitative measure of shaking at individual points within this area. Though formulas exist for converting intensities to accelerations, these conversions are not exact, as each intensity covers a range of accelerations.

All the components of a water system have a threshold value of shaking. When a component's threshold value is reached or exceeded the component is likely to become inoperational. Thus an indication of the degree of shaking at all locations is of importance, for it, coupled with the components' threshold values, will lead to the probabilities for the component consequences.

Usually key facilities of a water distribution system are housed in buildings. For any building it is possible to derive a value of acceleration which this building will be able to experience without sustaining major structural damage or collapse. Newer buildings have often been built for a certain design acceleration, which may be helpful in determining at which level of acceleration major structural damage or collapse will occur. Possibly similar threshold values can be obtained for some of the major pieces of equipment in the key facilities. Behavior of key facilities of water systems in past earthquakes may also give indications of their performance at various levels of shaking.

So far only key facilities subjected to shaking have been considered, but pipes are also liable to be damaged by shaking. Examples of damage in pipes due to shaking are joint loosening and "blowouts" (from fluctuating water pressure) at rust-weakened spots in steel pipes. Through future detailed studies it may be possible to arrive at threshold values for pipes. These threshold values would have to be dependent on pipe material, approximate pipe age, types of joints used, and on the general condition of the soil in which the pipe is embedded.

Taking the chosen earthquake and a suitable attenuation law, and coupling this with the knowledge of all the components' threshold values, it is possible, in a subjective way, to arrive at probabilities of occurence for each of the component consequences in the set of component consequences that is being used.

3.2.3 Ground Failures

The earthquake effect which in many cases most severely affects the functioning of a water distribution system is that of ground failure, be it liquefaction, differential settlement, landslides, or another form. This is apparent in several of the descriptions of earthquake damage in chapter 2, in particular in the case of the 1906 San Francisco earthquake.

One kind of ground failure is that of liquefaction, which is most likely to occur in areas of submerged man-placed fills, or in areas of naturally deposited, fine to medium, poorly graded, loose sands located below the ground water table. This kind of soil condition can be found in many large cities and metropolitan areas lying on rivers, since the need for space has led to the development of previously marshy and otherwise unsuitable land. Often this man-made land lies in close proximity to present river courses, though it may also be in locations where rivers previously had their beds.

After the development of this land, buildings were erected on it and the water distribution network was extended to serve these new areas. It is these areas of water distribution systems that warrant especially careful consideration. In some cases the water system may have simply been extended into the developed areas to provide water to these areas. In this case damage in this area would have an impact only on the area itself. However, major distribution pipes, serving large parts of the water system, may have been laid through the man-made area, using it as a convenient corridor. Ground failure-induced damage to these pipes would not only affect the area itself, but would have a major impact on all those parts of the water network which are supplied via these pipes.

Taking the chosen earthquake, and using a recently developed method of analysis (Yegian, 1976), it is possible to determine the probability of ground failure due to liquefaction in any area of "poor" soil at a given distance from the earthquake's location. Probabilities of other kinds of soil failures will have to be based on experience from past earthquakes if quantitative methods for deriving these probabilities can not be found.

Once the probabilities of ground failures within the area which encompasses the water system are known, it must be determined what component consequences each of the possible ground failures would entail. This can be accomplished by making the assumption that any key facility or any section of pipe within an area of ground failure will be rendered inoperational.

When all of these steps have been completed, probabilities for the various component consequences in the set being used will again have been obtained.

3.3 System Consequences

Each of the component consequences being used, whether in a limited or in a more extended set, does not in itself give an indication of how the whole system will be affected. The determination of the system consequence(s) corresponding to each component consequence is the next step in this system analysis.

A problem that arises when trying to evaluate system performance is that of choosing a point in time after the earthquake for which to convert component consequences into system consequences. It is obvious that for any level of damage in a system the immediate system consequences are more severe. With the passing of time adjustments can be made to the system; that is, available auxiliary facilities can possibly be used to perform some of the functions of damaged key facilities, damaged sections of pipe can be blocked off by the use of gate valves, and rerouting of water supplies can be implemented. For a first analysis of a water system it is the immediate system consequences which are of most importance, because adequate water supply will then be most critical in emergency efforts, such as fire-fighting.

The best approach to assessing system consequences would lie in the use of a dynamic flow model for a water distribution system. Each component consequence could then be simulated and the resulting effect on the water supply, in terms of the reduction in quantity and pressure, could be monitored at any chosen point in the network. A flow model would also permit a study of the change of system consequence with time for each given component consequence, since the blocking off of damaged pipes, etc., could also be modeled.

If a flow model is not available for the network under consideration, then a much more subjective approach has to be taken to evaluate system consequences. System consequence, since related to component consequences, is also a continuous spectrum, ranging from no or negligible effects on the system's functioning to complete breakdown of the system. This spectrum of system consequences can be broken into a set of discrete categories of system impact, such as no/negligible, minor, moderate, major, and catastrophic. Each of these categories must then be described in qualitative terms, indicating what level of service the system is still capable of providing.

Each individual component consequence in the set considered needs to be viewed in terms of the impact which it will have on the overall performance of the system. The prerequisite for this is a basic knowledge of the water system's layout and overall functioning. With this knowledge the transition from component consequence to system consequence can be made.

In this transition it will be found that a component consequence may not always entail the same system consequence. This is particularly true for component consequences dealing with damage to pipes. A given percentage of pipe damage, depending on its distribution within the water system, will have different impacts on the system. Due to these variations in system consequence for a given component consequence, an analysis needs to be carried out for each component consequence to determine the probabilities of the various system consequences that it may entail. This analysis may be done by hypothesizing a sufficiently large set of the same component consequence, and determining the relative frequency with which each system consequence results. When this has been completed for each of the component consequences, the system consequences for a given earthquake can be evaluated. Suppose, as an example, that for a given earthquake a movement of 5 feet along a known fault has a probability of 0.3, that no movement has a probability of 0.7, that 5 feet of movement would result in a component consequence of 20% of the pipes being damaged, and that no movement results in no damage. Further, suppose it is found that the component consequence of 20% of the pipes damaged results in minor system consequence 70% of the time, and in moderate system consequence 30% of the time. Then the system consequences due to faulting would be as follows:

No/negligible	= 0.7 * 1.0 = 0.70
Minor	= 0.3 * 0.7 = 0.21
Moderate	= 0.3 * 0.3 = 0.09
	Sum = 1.00

The above steps can in principle be carried out for any earthquake under consideration, and three sets of probabilities for system consequences will be found, one set for each of the direct earthquake effects. From the probabilities in the three sets it may be directly obvious that one earthquake effect is the governing one; that is, if the more severe system consequences in one set have much higher probabilities assigned to them than in the other two. In this case, the most severe set of probabilities may be taken as that which describes the functioning of the system.

However, if none of the sets of system consequences is obviously dominant, then the two more severe ones, or possibly all three, have to be combined to reflect the increase in severity due to the combination of earthquake effects. In order to accomplish this the component consequences for each earthquake effect need to be reexamined and compared. This comparison may show that the damages leading to the same component consequence for different earthquake effects are very different, and are thus, when combined, much more severe. Using the comparisons and the knowledge of the system's layout and functioning, probabilities of system consequences for combined earthquake effects may be obtained. These probabilities may vary somewhat for different persons doing the same analysis as they are based on personal judgement. More severe system consequences will have increased probabilities and less severe ones will have lower probabilities, reflecting the combination of different earthquake effects.

CHAPTER 4

A GENERAL DESCRIPTION OF THE METROPOLITAN DISTRICT COMMISSION WATER SYSTEM

4.1 Purpose

As was indicated in chapter 3, parts of the methodology developed in that chapter are to be applied to a real water distribution system, in order to evaluate the impact of ground failures on the functioning of the system. For this purpose the Metropolitan District Commission (MDC), Commonwealth of Massachusetts, water distribution system was chosen.

The MDC water system does not supply consumers directly, but rather it supplies cities, towns, and municipalities, which then supply individual consumers using their own distribution systems. Thirty-four cities and towns in the Metropolitan Water District, lying within a 15-mile radius of the Boston State House, are completely or partially supplied by the MDC system. A further ten municipalities, which are not members of the District, also receive all, or a portion, of their water supply from the MDC water system (MDC - Metropolitan Water System, 1974).

In the event of an earthquake, possible damage to the MDC water system may seriously jeopardize the water supply of the various cities and municipalities. This chapter will give an overall description of the present MDC water system (some more detail about the older parts of the system may be found in a description by Brackett, 1906), and will indicate which earthquake effects may threaten the various parts of the system. A description of general soil conditions in the Metropolitan

Water District will also be included. The next chapter will describe the parts of the analysis that were carried out.

4.2 Main Features of the MDC Water System *

The MDC's water supply comes principally from the Quabbin, Ware River, and Wachusett Reservoir watersheds (see Figure 4.1). During peak consumption periods, water is also utilized from the Sudbury system. Average water consumption is 320 million gallons per day (mgd). The Quabbin Reservoir, 530 feet above Boston city base, is the furthest from the District, located at a distance of about 65 miles from the Boston State House.

4.2.1 Water Delivery System

Quabbin Aqueduct, a deep-rock tunnel, connects the Quabbin and Wachusett Reservoirs. It has a capacity of up to 610 mgd, and it also serves in conveying water from the Ware River intake to either the Quabbin or Wachusett Reservoir.

Water is carried from the Wachusett Reservoir, which is at an elevation of 395 feet above city base, in two aqueducts. The deep-rock Wachusett - Marlborough Tunnel, completed in 1965 (380 mgd), conveys water to the Hultman Aqueduct intake structure at Marlborough, whereas the Wachusett Aqueduct, basically a brick and stone masonry aqueduct built in 1898 (250 mgd), is used as needed for carrying water to either the Hultman Aqueduct or to the Sudbury Reservoir.

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* Information about the MDC water system was obtained in part through interviews with Mr. J. Sargent, Senior Civil Engineer in the Water Division of the Metropolitan District Commission.

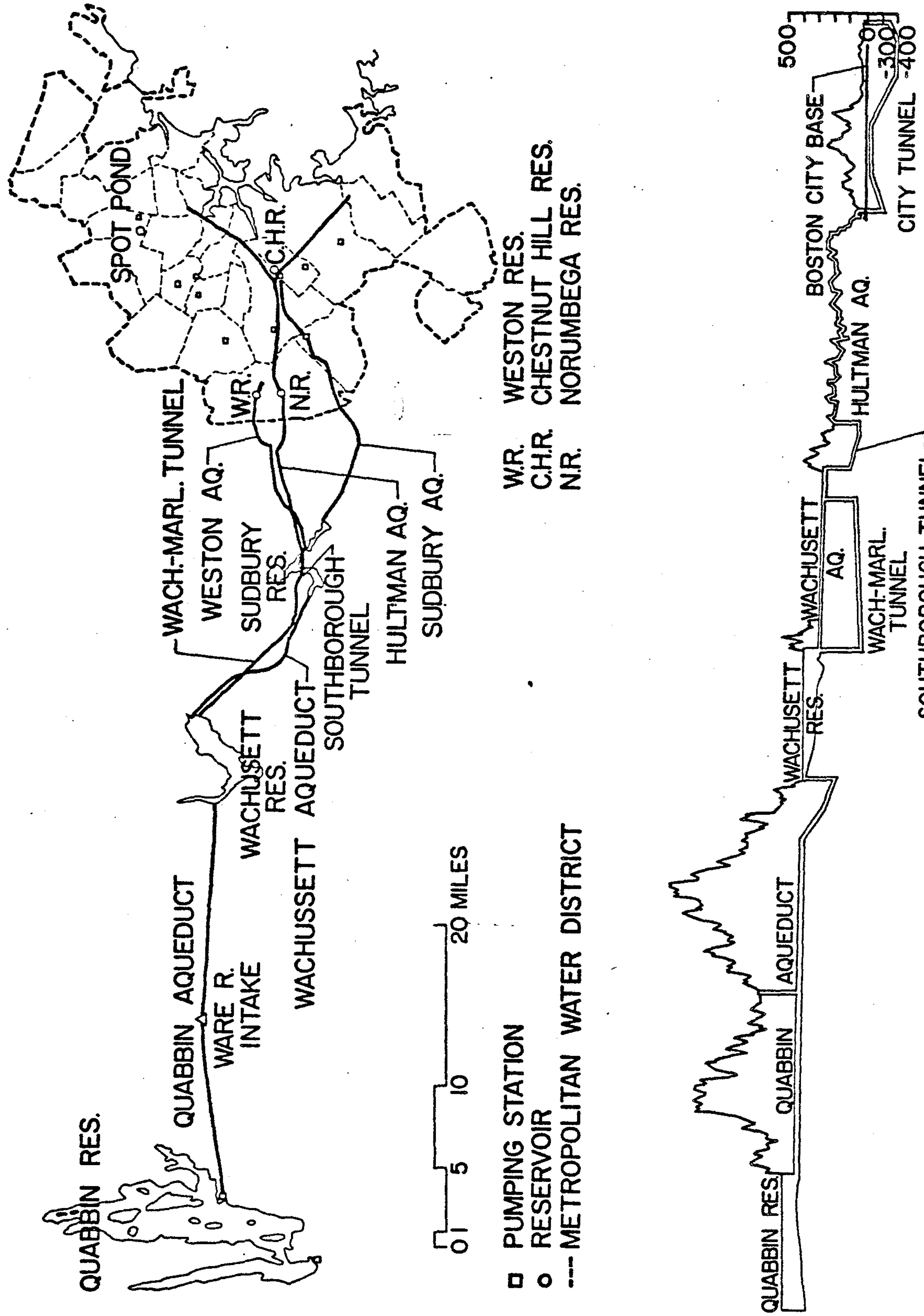


Figure 4.1 - General Plan of the M.D.C. Water System
(MDC - Metropolitan Water System)

Three aqueducts are available to carry water over the final section of the supply route into the District. The Hultman Aqueduct, in service since 1940 (325mgd), runs for three miles through the Southborough Tunnel, and carries water to the Norumbega Reservoir, at 274 feet above city base, and from there to the downtake shaft of the City Tunnel. It supplies approximately 80% of the needed water. The Weston Aqueduct of 1903 vintage (300 mgd), extending from the Sudbury Reservoir to Weston Reservoir (200 feet above city base) and from there into the District's distribution network, supplies the remaining 20% of the water. Usually the Weston Aqueduct carries 50 mgd diverted from the Southborough Tunnel, but it can also take water from the Sudbury Reservoir. The Sudbury Aqueduct, dating back to 1878 (90 mgd) and connecting the Sudbury Reservoir to the Chestnut Hill Reservoir, is used during summertime high demand periods.

The delivery system's major link into the interior of the District is the 5-mile long City Tunnel, a deep-rock tunnel connecting the Hultman Aqueduct's terminal shaft by the Charles River in Newton with the Chestnut Hill Reservoir. At this point water can be fed into large distribution mains, or it can be conveyed further by means of two additional tunnels. Extending north to Malden is the 7.1-mile long City Tunnel offshoot, and running to Dorchester Lower Mills, by the Boston - Milton line, is the 6.6-mile long Dorchester Tunnel.

Because of the nature of the facilities described so far, it seems likely that they would be rendered inoperational only if one of two earthquake events were to occur. The first would be an earthquake causing severe ground shaking (say accelerations of 0.2 g, or greater) at the surface aqueducts. The severity of shaking might then be sufficient to damage the surface aqueducts. The second would be an event involving faulting near the aqueducts, thus possibly damaging surface aqueducts or even deep-rock tunnels. Judging from the history of earthquakes in Massachusetts, it seems unlikely that such intensity of shaking, or such faulting, as would damage aqueducts and deep-rock tunnels, will occur.

4.2.2 Pipes in the Distribution Network

The MDC water distribution system has a network of approximately 250 miles of water mains, 96% of them ranging from 16 to 60 inches in diameter. The location of most of these mains is shown in Figure 4.2. The main running from Weston Reservoir northeast to Waltham, Belmont and Arlington, is for the most part made up of 60-inch diameter steel sections with lock joints, embedded in the ground below the frost line. Another 60-inch main runs from the Weston Reservoir towards the Charles River in Newton, and then close to the Charles River through Brighton. This main is also mainly made up of steel sections. The two mains connecting Weston Reservoir and Chestnut Hill Reservoir, 48-inch and 60-inch pipes, consist of a mixture of cast iron and steel sections. A detailed description of all the pipes in the MDC water system is beyond the scope here attempted.

Earthquake-induced ground failures probably pose the greatest danger to the integral functioning of the pipe network. As will be shown in section 4.3, areas of poor soil exist in the District, and many pipes run through these areas. For any earthquake causing a sufficient intensity of shaking in these areas of poor soil to cause ground failures, pipe

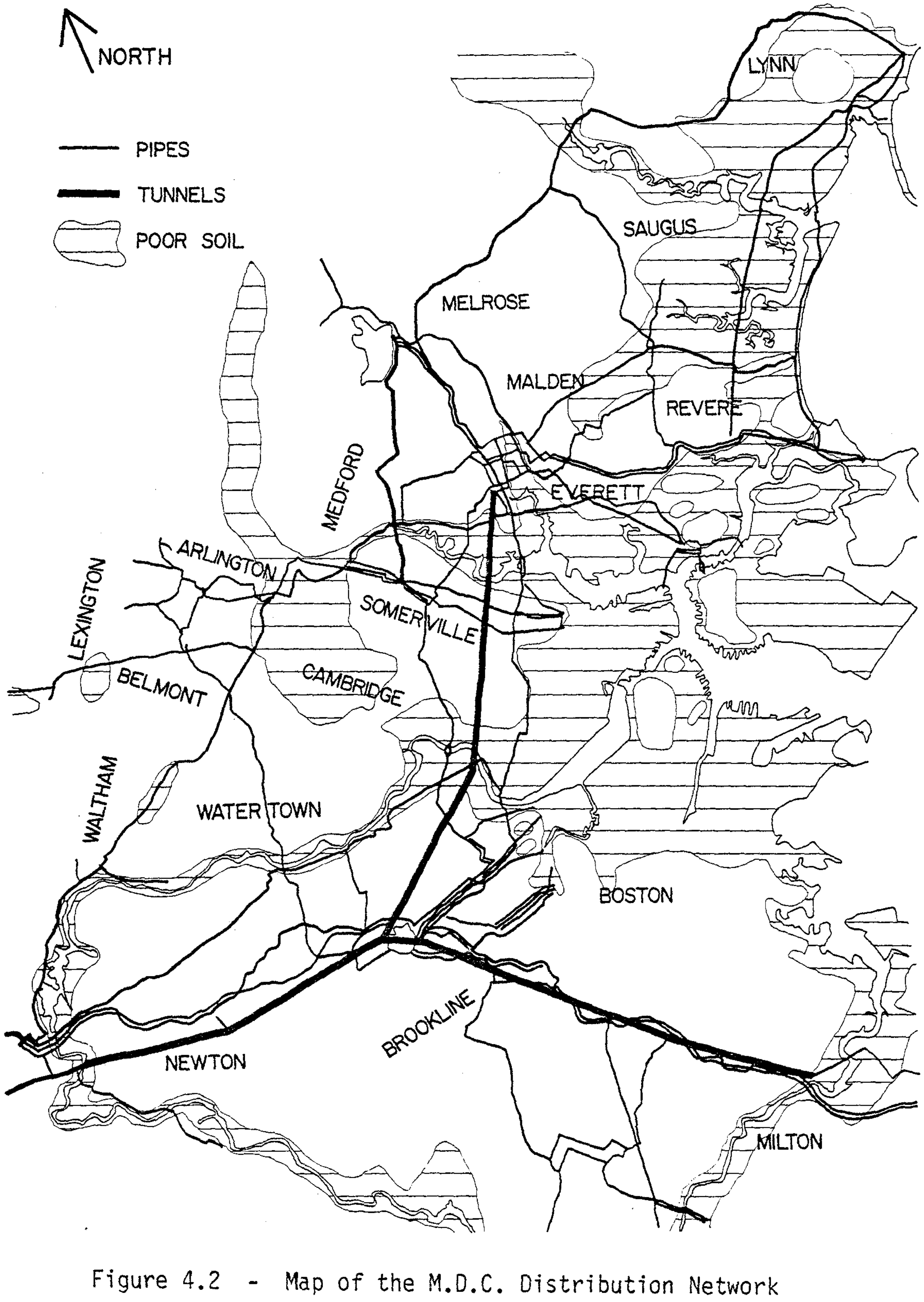


Figure 4.2 - Map of the M.D.C. Distribution Network

failures may result.

4.2.3 Pumping Facilities

The pipes shown in Figure 4.2 constitute six individual distribution systems with various pressure levels. Pressure is normally maintained by the natural head existing in the water coming from the Weston Reservoir for the low pressure services and from the Norumbega Reservoir for the high pressure services. There are 12 pumping stations in the MDC water system. Most of them are operated on a daily basis to maintain the needed pressure in the various service networks. Among the 12 stations are the following: one pumping station each in Needham, Hyde Park, Newton, Waltham, Belmont, Brookline, at Chestnut Hill Reservoir in Brighton, and at Spot Pond in Stoneham. Two pumping stations in Arlington are used for the northern extra high service. In the event of the City Tunnel being inoperational, the pumping stations at Chestnut Hill Reservoir and Spot Pond would be the only means of feeding the high pressure services. The pumping stations all have their own diesel back-up power.

All pumping facilities are at locations where ground failures would most likely not be the critical earthquake effect.

4.2.4 Distribution Reservoirs and Treatment Facilities

Scattered throughout the District are 14 distribution reservoirs, varying in size from 1838 to 2 mg. The largest is Spot Pond (1838 mg), but its use is limited by its elevation (163 feet above city base) and a small pumping facility. Other distribution reservoirs are Chestnut Hill

Reservoir (523 mg), Weston Reservoir (200 mg), Norumbega Reservoir (150 mg), Bear Hill Reservoir, Blue Hill Reservoir, and Fell Reservoir.

Treatment facilities exist at Weston and Norumbega Reservoirs, and also at open distribution reservoirs, such as Chestnut Hill, Spot Pond, Fell, Bear Hill, and Blue Hill Reservoirs. Should damage be sustained by the Norumbega or Weston Reservoir treatment facilities, this would not necessarily mean that the water supply from these sources would be cut off. Rather, the actual treatment facilities could be by-passed, and water could still reach the District. Thus water could be available for emergency efforts, such as fire-fighting, but it would need to be sufficiently boiled before being safe as potable water.

4.3 Soil Conditions in the District

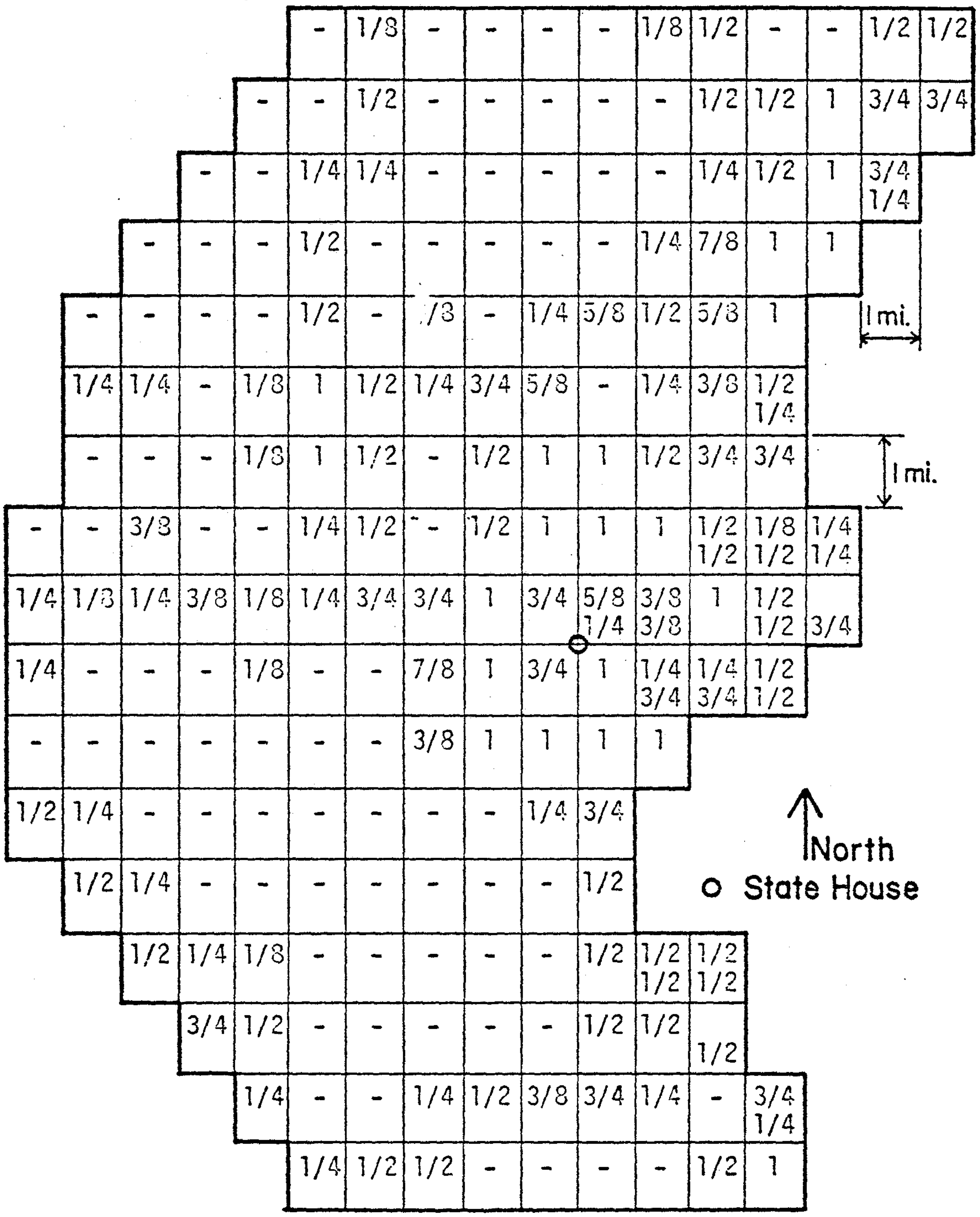
In the event of an earthquake, the pipes of the distribution network are likely to be the most vulnerable components of the MDC water system, in particular those pipes which are located in areas of poor soil. This judgement is based on the description of the system in section 4.2 and on the performance of water systems in past earthquakes as described in chapter 2.

There is a considerable area of poor soil in the District, the extent of which is shown in Figure 4.2. The soil overlying bedrock in the Boston area may be roughly divided into three types: "made land," "waterlaid deposits," and "glacial till" (Crosby, 1923). "Made land" has already been described in chapter 3. "Waterlaid deposits" applies to deposits both of glacial or recent origin, and "glacial till" is the unstratified material deposited by the ice sheet which once covered the region, consisting of boulders, pebbles, sand and clay. The term "poor soil" (or "bad ground"), as used here, designates made land and unconsolidated waterlaid deposits saturated with water. Frequently, this poor soil is in locations where there is an unsupported edge, such as a river bed, towards which the soil could move during an earthquake.

Any map showing the Boston area during the mid-1600's will indicate how much of the land existing today has been man-made. Extensive areas of man-made land are situated in the valley occupied by the Merrimack River in preglacial times. This valley extends from the Mystic Lakes, past Fresh Pond, through Allston and the Back Bay, to the old harbor in the South Cove, south of present-day South Boston.

Poor soil, in some places even marshy land, may be found along the Chelsea Creek, and along the Saugus, Malden, Mystic, Charles, and Neponset Rivers, in particular in areas where these rivers used to have their effluence. Another large marshy area is in the Saugus swamps.

The area which encompasses the pipe network of the MDC water system was chosen as shown in Figure 4.3. This area, including the surface areas of lakes and rivers, measures 200 square miles. Of this area approximately one-third may be considered poor soil.



x	fraction of the area which consists of poor soil
y	fraction of the area which consists of water

Figure 4.3 - Areas of Poor Soil in the Water District

CHAPTER 5

SYSTEM CONSEQUENCES OF GROUND FAILURES FOR THE MDC DISTRIBUTION NETWORK

5.1 Introduction

As was pointed out in chapter 4, about one-third of the ground in the District is bad ground. Using the original on which Figure 4.2 is based (a 42 by 50 inch blueprint map), 56 miles of the MDC's distribution pipes were found to be in this poor soil. This represents nearly one-fouth of all the pipes.

In this chapter an analysis will be made of the system consequences resulting from various levels of damage to the pipes in poor soil. Assumptions made will be stated first, then the set of system consequences will be defined, and finally an outline of the analysis, as it was carried out, will be given. The results of the analysis will also be stated.

5.2 Assumptions

Several simplifying assumptions were made to decrease the complexity of the analysis of pipe damage and the resulting system consequences.

First, the length of a pipe section which can be blocked off by two gate valves was taken to be one mile. This is a conservative length, as usually there are gate valves every few thousand feet along a pipe line. The pipes in poor soil were modeled by one-mile sections werever possible. However, sometimes the sections were slightly longer to avoid having a remaining pipe section of very short length, while at other times shorter sections had to be used due to the layout of the pipes. For example, connecting pipes between two mains running closely parallel to each other had to be modeled by short sections. Thus pipe sections ranged from 0.15 to 1.36 mile in length, with an overall average length of 0.65 mile.

Second, for this analysis, the MDC water system was taken to be one network, even though there are several distribution networks, one for each of the different pressure levels. System consequences were evaluated assuming all networks to be interconnected. In the actual case interconnection does not always exist, as, for example, a low pressure pipe could not feed a high pressure network.

In the analysis that was carried out the effect of component consequences on system consequences was evaluated. The starting condition was always stated as follows: If ground failures were such that x% of the pipes in poor soil are damaged, what are the system consequences. But the component consequence "x% of the pipes in poor soil damaged" depends on the severity of ground failures, which in turn depend on the earthquake event. An approach to determine these interrelationships might involve several further assumptions.

The assumption may be made that all of the District will experience the same intensity of shaking during a given earthquake. This is in most cases not actually true, as usually two or three zones of intensity would exist. However, in a very conservative approach, the highest of the various intensities could be taken to affect the whole District. Dealing with only one intensity in a first analysis is desirable, as it will lead to only one set of probabilities for the different levels of severity of ground failure, and these probabilities will be applicable to all of the bad ground in the District. If more than one intensity is considered, then the sections of pipe failing due to ground failure will no longer be randomly distributed over the pipe network in bad ground, as they may be for only one intensity (this is shown below).

For any level of severity, say y% of the poor soil failing, it can be assumed that the extent of each ground failure covers an area of one square mile (or any other appropriate size), and that the total number of one square mile areas constituting the y% are randomly distributed over the whole area of poor soil. Simulating the random distribution of y% of the poor soil failing a sufficiently large number of times, probabilities for various levels of pipe damage in poor soil may be obtained. Because the one square mile areas are taken to be randomly distributed, the damaged sections of pipe will also be randomly distributed over the pipe network in bad ground. This also implies that pipe sections are independent of each other.

5.3 Analysis of System Consequences

As was indicated in chapter 3, a set of system consequences needs to be chosen and each individual system consequence must be described qualitatively to indicate what level of service the system can still provide. The following system consequences were chosen for the MDC water system:

No/negligible - damage to the system is such that it is still fully operational, providing a full supply of water to all communities.

Minor - water can be supplied to all communities, though blocking off of damaged sections and rerouting of water is necessary; volume and pressure of water may be reduced immediately after the earthquake.

Moderate - one community at the edge of the network is virtually cut off from the water supply; or several major mains supplying a whole sector are inoperable and substantial rerouting is necessary, involving a reduction of water volume into that sector.

Major - several communities on the edge of the network or a whole sector are experiencing difficulty in receiving a sufficient supply of water, even after rerouting has been implemented.

Catastrophic - breakdown of the system, all communities are receiving insufficient supplies of water, rerouting is futile as all strategic mains have sustained damage.

The next step in the analysis of the MDC water system was to choose certain component consequences which might result from ground failures. The following were chosen: 5%, 10%, and 25% of the pipes in poor soil are rendered inoperational. The percentage indicates how much of the total length of the pipes in poor soil is non-functional due to ground failure damage. The probabilities of ground failures resulting in these amounts of pipe damage may be evaluated as outlined in sections 3.2.3 and 5.2.

For each of the component consequences the damage was taken to be randomly distributed over the pipe sections in bad ground, because it is assumed that ground failures will be randomly distributed in areas of bad ground having the same intensity (see section 5.2). The damage corresponding to each component consequence was simulated 10 times. All the pipe sections in bad ground, ranging in length from 0.15 to 1.36 miles, were numbered consecutively from 1 to 87. A random number generating scheme was then employed in picking "damaged" sections until the cumulative length of the chosen sections corresponded to the component consequence under consideration.

The sections chosen as inoperational in each simulation were marked on an overlay which was placed on the map of the complete MDC distribution system. By inspecting the locations of the damaged sections, considering the size (diameter) of the damaged sections, and evaluating their relative importance, a judgement was made as to the system consequence that would be entailed by the damaged sections. (For an example of the simulations see Appendix A.)

The results of all simulations (ten for each of the three component consequences considered) are shown in Figure 5.1. With even more simulations of each component consequence it may be possible to obtain an even more detailed distribution of system consequences.

It should be remembered that the percentages in the component consequences only indicate the extent of damage to pipes in bad ground. Thus 25% of the length of pipes in bad ground damaged corresponds to approximately 6% of the total MDC network damaged, as roughly one-fourth of the total network is in bad ground.

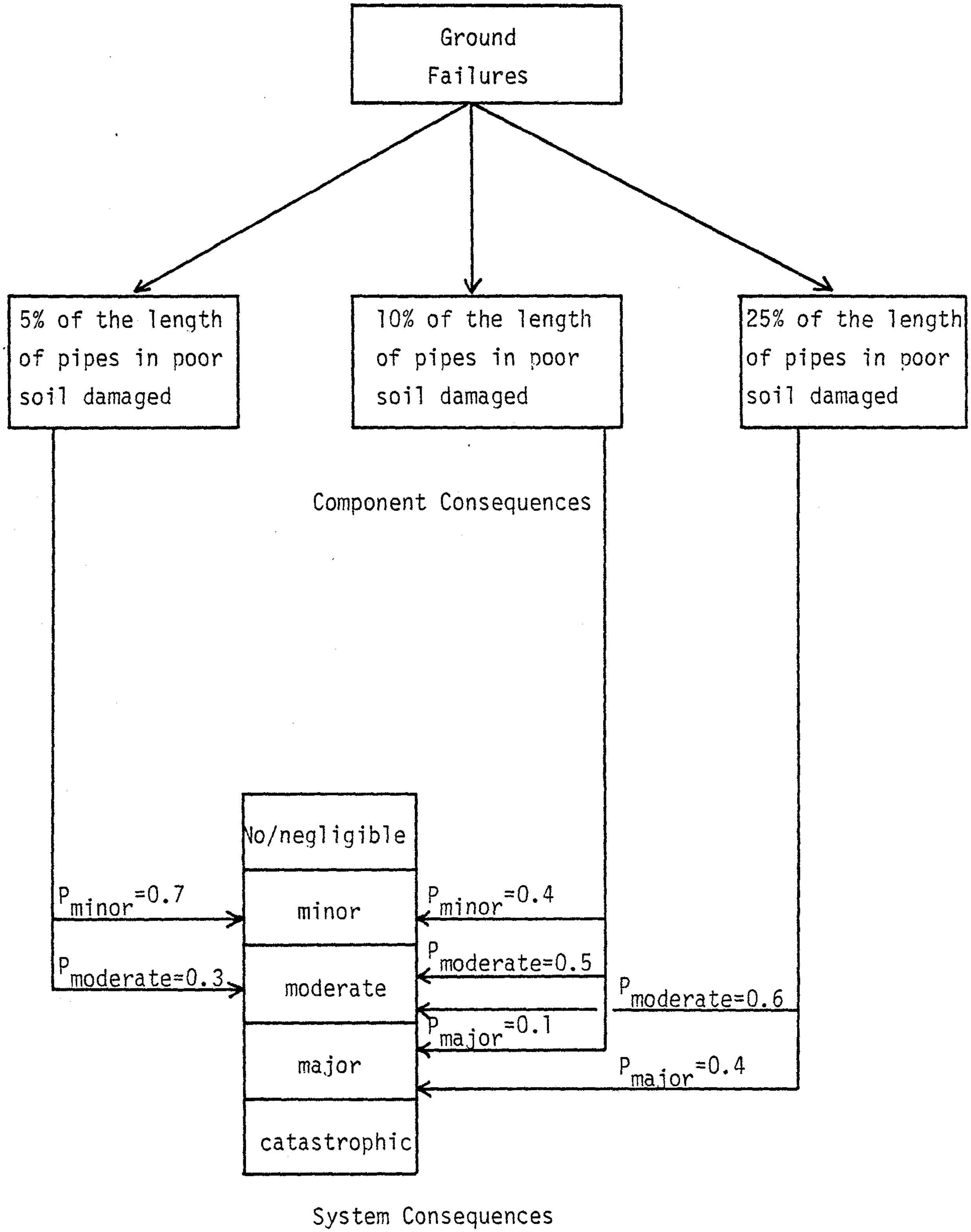


Figure 5.1 - Component and System Consequences for the MDC Water System

5.4 Conclusions

The above analysis demonstrates the severe impact that earthquakes and resulting ground failures may have on a water distribution system which has parts of its network in poor soil. No such system will be completely rebuilt in order to reduce the impact of earthquakes. However, when the network is expanded, or parts of the existing network are replaced and upgraded, several recommendations should be considered in the design, for they may ameliorate the impact of ground failures.

Whenever possible, areas of bad ground should be avoided. If this is not feasible, then the design of the pipeline which is to cross poor soil should provide for large amounts of movement. Important supply pipes should be laid in duplicate along widely separated routes to increase the redundancy in the network.

Gate valves should be generously distributed throughout the pipe system, for they are instrumental in blocking off damaged pipe sections and in rerouting of water.

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APPENDIX A

EXAMPLES OF PIPE FAILURE SIMULATION AND DETERMINATION OF SYSTEM CONSEQUENCES

Two of the ten simulations for 25% of the pipes in poor soil having failed due to ground failures are here described.

In simulation case 1 a total of 18 pipe sections in poor soil were chosen (by a random number process) to have failed due to ground failures, and 23 pipe sections were chosen in case 2. The cumulative length of the "failed" pipes sections in each case is 25% of the total length of pipes in poor soil, which corresponds to about 14 miles of pipe being inoperational. The general locations of the pipe failures for the two simulation cases are shown in Figure A.1 and Figure A.2. In these figures the length of each "failed" pipe section is not given. The critical aspect of the failures is their locations, for the locations determine what system consequence will result.

Case 1 is taken to entail a "moderate" system consequence. Though none of the communities at the edge of the network is cut off from its water supply completely, Milton and Swampscott (northeast of Lynn) each have two of their supply pipes nonoperational. Extensive rerouting would be necessary if the simulated pipe failures were to occur, especially due to "failed" pipe sections in Waltham and in Cambridge (crossing the Charles River), and thus communities north of the Charles River might experience shortages in water supply for some time after these pipe sections failed.

Case 2 is more severe, and is taken to entail "major" system consequences. Milton now has three of its supply pipes damaged. But of even

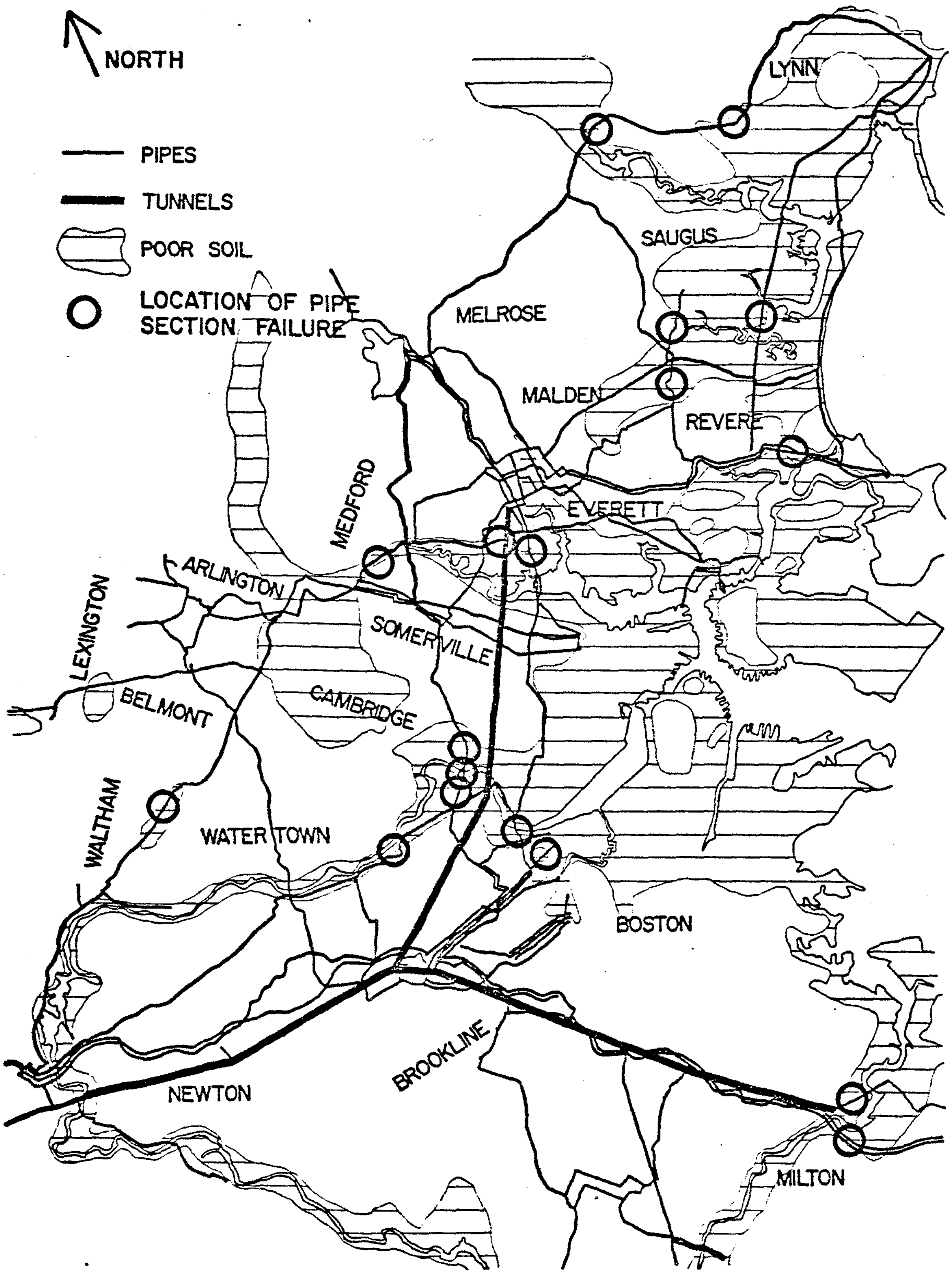

Figure A.1 - 25% Pipe Failure in Poor Soil: Simulation Case 1

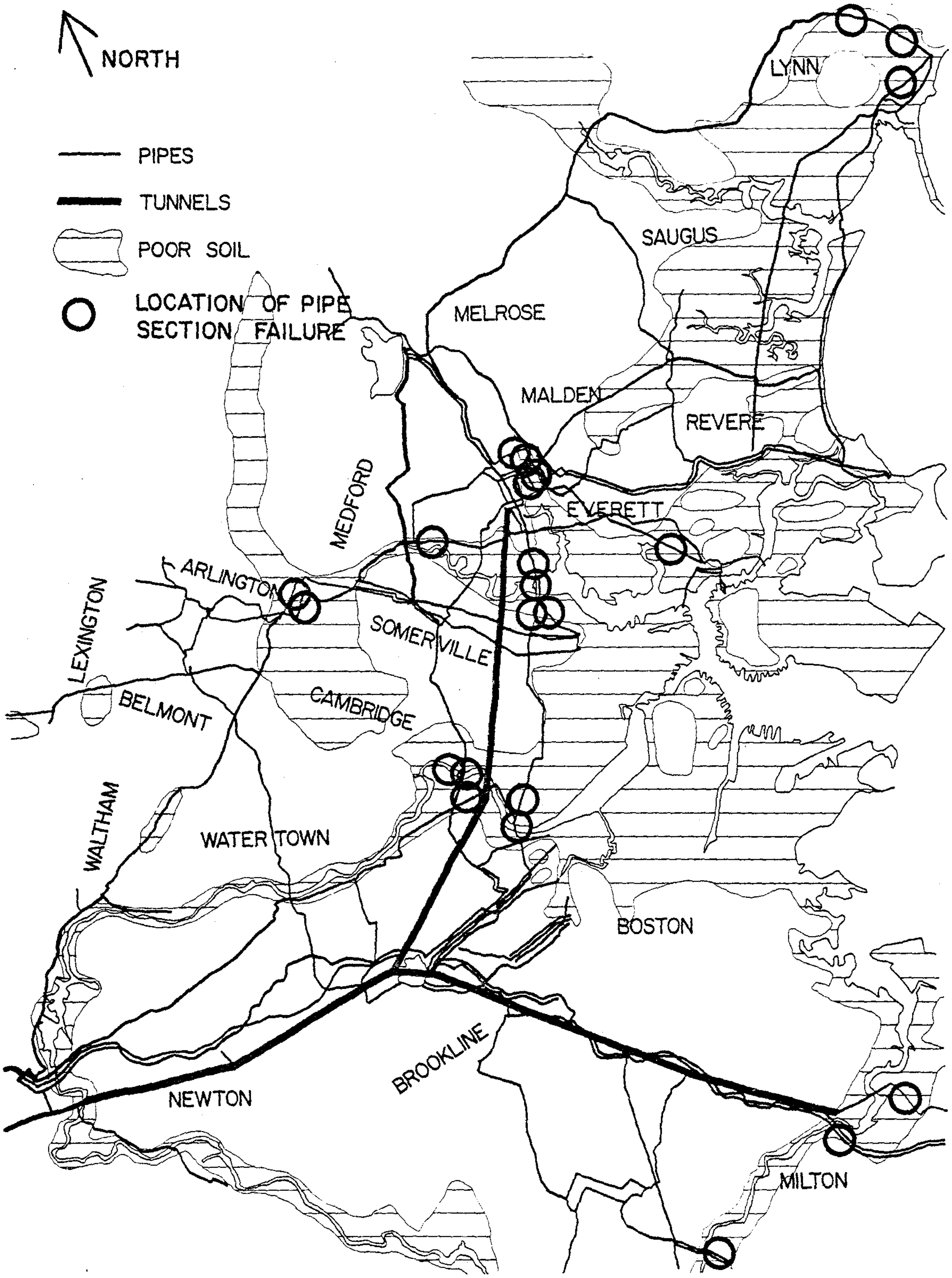

Figure A.2 - 25% Pipe Failure in Poor Soil: Simulation Case 2 greater impact is the fact that the whole northeastern sector of the network is isolated from the rest of the distribution network (roughly the area north of a line drawn from Arlington to the Cambridge-Watertown line on the Charles River, and from there along the river to the ocean). All supply routes into this sector have been damaged, and water could only be supplied to communities therein through extensive rerouting from the tunnel (if operational) and from Spot Pond. Immediately after the earthquake causing this damage extensive water shortages would probably exist in this whole sector. Two of the three supply pipes to Swampscott are also damaged, so that its water demand could probably not even be covered after rerouting.

Ten of these simulations were carried out for each of the component consequences (5%, 10%, and 25% pipe failure in poor soil), and using subjective judgement the results shown in Figure 5.1 were obtained.

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