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DEVELOPMENT OF METHODOLOGY FOR RETROFITTING WATER LIFELINES FOR IMPROVED SEISMIC RESISTANCE

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The main objective of this study was to develop a methodology to evaluate and apply retrofitting procedures to provide seismic protection to existing water systems in the United States. This report is concerned with the seismic protection of existing water lifeline systems (i.e., post-construction measures). The study includes a review of historical data on water system damage and failures caused by earthquakes. Existing codes and seismic evaluation methods for building and/or utilities were reviewed for application to existing water systems. Potential retrofitting techniques and associated preliminary designs are identified. Emphasis is on the utilization of the existing state-of-the-art knowledge of earthquake forces to develop a methodology for evaluating water system impacts and identifying methods to mitigate or minimize damage to critical systems. Cost factors for implementation of the retrofit techniques are identified in an effort to emphasize the cost/benefit principles involved in planning a retrofit program.

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Chapter I

Introduction

Background

The objectives of a municipal water system are to provide safe, potable water of sufficient quality, quantity and pressure to meet the needs for domestic use, fire fighting and commercial/industrial uses. A reliable water supply is essential for the maintenance of public health, fire safety and economic stability in a populated (urban) area. The Federal, State and Municipal authorities have long realized the importance of developing and maintaining public water supplies, having invested billions of dollars in construction and operations and maintenance of these systems. As a society we have become dependent upon an uninterupted public water supply.

Earthquakes are one of the most violent forms of natural disater and are capable of causing massive destruction to unprepared communities. Earthquakes in the United States and abroad have often caused debilitating damage to lifeline systems causing in some instances long term disruption of these services. Studies of recent strong earthquakes, such as the San Fernando earthquake of 1971, have led to the recognition that earthquake engineering has to be strengthened in the public utilities or lifeline fields. Lifelines are those systems that are essential to public safety, health and maintenance of lifestyles such as energy, transportation, communication, sewerage and water supply systems. The consequences of damage to water systems has resulted in loss of life due to fire and disease and caused extensive economic losses. Experience gained from past earthquakes reveals that increased protection against earthquakes can be provided by improving the capability of these vital systems to withstand earthquake induced forces.

To date, emphasis in the development and application of earthquake mitigation techniques has been primarily aimed at new construction. These techniques have generally been developed for building design and construction such as the Uniform Building Code (UBC). It has only been recently that lifeline systems have been evaluated with respect to seismic impact. The National Science Foundation (NSF) and the Technical Council on Lifeline Earthquake Engineering (TCLEE), Americal Society of Civil Engineers have been instrumental in stimulating research and information transfer on lifeline earthquake engineering. These efforts, as with building design have generally dealt with aseismic techniques at new systems. Exemplary of these efforts is the NSF sponsored study "Earthquake Design Criteria for Water Supply and Wastewater Systems", 1980 by EQSI (1).

This report is concerned with the seismic protection of existing water lifeline systems (i.e., post-construction measures). The main objective of this study was to develop a methodology to evaluate and apply retrofitting procedures to provide seismic protection to existing water systems in the United States. This project was the logical "next step" in the state-of-the-art development of techniques available to ensure that water supply systems continue to perform as required with minimal disruption from earthquake activity.

This study includes a review of historical data on water system damage and failures caused by earthquakes. In addition, existing codes and seismic evaluation methods for building and/or utilities were reviewed for application to existing water systems. Potential retrofitting techniques and associated preliminary designs are identified. Emphasis in this report is on the utilization of the existing state-of-the-art knowledge of earthquake forces to develop a methodology for evaluating water system impacts and identifying methods to mitigate or minimize damage to critical systems. Cost factors for implementation of the retrofit techniques are identified in an effort to emphasize the cost/benefit principles involved in planning a retrofit program. It is expected that this report will function as an introduction to seismic impacts on water lifeline systems and be a guide to decision making for the local utility in determining if retrofitting is needed and if it is, where retrofitting money can best be spent. To this end, the report is directed to municipal authorities, utility managers and water supply engineers.

Basic Approach

In the United States, earthquakes of destructive magnitude are generally associated with the western states, specifically Alaska and California. It is true that this area has the highest incidence of earthquakes but they certainly are not limited to this region of the U.S. Major eqrthquakes have occurred in

New England, the Southeast and in the Midwest during the relatively short period of recorded history (i.e., in geologic terms). The limited amount of data available on the frequency and magnitude of earthquakes in the U.S. as well as the embryonic state-of-the-art of earthquake prediction requires a national recognition of the destructive potential of earthquakes. The potential vulnerability of lifeline systems such as water supply need to be evaluated such that levels of risk can be analyzed and reduced if found to be significant.

The purpose of this project is to develop a methodology that can be directly useful in evaluating the risk and vulnerability of a water supply system to earthquake activity. It also provides means by which the existing facilities can be modified to reduce the risk or extent of water supply system failure after a moderate to major seismic event.

The information presented is based upon the following general sources:

1. Reports of earthquake damage to utilities (water, electrical, communication).

2. Seismic design codes and regulations for buildings and associated equipment, including existing and proposed codes.

3. Theoretical analyses and studies of the response of related equipment to seismic motion.

4. Emergency response guidelines and plans for water supply systems.

These sources of information have generally addressed structural and to a lesser extent, architectural components of buildings. Methods of design and retrofitting of these structures to resist seismic damage is related to prevention of building failure or collapse, with the overriding purpose of preventing loss of human life due to structural failure. Water lifelines do not consist of only structural and architectural building components, though these certainly are an integral part of the system. Water systems are also comprized of endless combinations of tanks, pipes, and electrical and mechanical equipment. In addition, unlike a building these systems are spacial dispersed through a geographic area with varying degrees of seismic influence. Experience from previous earthquakes has shown that the nonstructural equipment required for the operation of water supply systems are commonly unable to perform their designated functions after an earthquake, even if the buildings housing the equipment sustain little or no damage. This experience clearly indicates a different set of criteria and design standards must be developed for the protection of this vital equipment. Therefore conventional static analysis of water lifeline components is often insufficient for a seismic modification. As a result, this study was dependent on utilization of only that fraction of earthquake design/modification data that realized this basic difference. Since dynamic modelling of equipment is very expensive and beyond the scope of this project, actual earthquake induced equipment failure data and limited 'shake-table' data were utilized to evaluate the seismic vulnerability of a water supply systems components and develop aseismic retrofit techniques.

At the present time, the state-of-the-art does not provide for accurate predictions of the local occurrence and physical manifestations of earthquakes and the corresponding impacts on specific water supply systems. Without a dependable means of local risk analysis, the engineer and utility planner must develop alternative means of rationalizing different levels of seismic strengthening. On one hand, most water lifeline systems in earthquake prone areas are probably underprotected. On the other hand, total protection of all equipment would be prohibitive both technically and economically. A method is presented in this report that identifies critical equipment that should receive primary attention. This is done by developing a general framework of system evaluation consisting of the following steps:

- Identification of overall performance goals of the system.

- Performance of a functional analysis of all those functions and subfunctions that are required to meet the performance goals.

- Identification of all equipment that corresponds to each subfunction.

- Rating the equipment according to its importance in meeting overall system goals to identify critical equipment.

- Evaluation of critical equipment to determine those most vulnerable to damage due either to direct or secondary seismic impacts.

These procedures allow for a systematic review of water supply system. It provides the framework whereby the engineer or utility planner can set goals to meet the needs of a specific system to achieve post seismic event system reliability.

In many instances there are water supply system modifications that can be instituted that do not require detailed seismic evaluation or extensive retrofit procedures. Often these include simple equipment tie-downs and attachments. In addition the installation of redundant components and bypass systems also reduce the impact of moderate to major earthquakes on essential operations of water supply systems. Identification of procedures that do not require extensive seismic evaluation are presented in this report. Many of these installations or modifications can be completed by the water utility personnel with only a minimum of seismic evaluation required by earthquake engineering experts. This enables a water utility to initiate an effective seismic retrofit program at minimum cost. These types of procedures have been stressed in this report because they have been shown to be cost effective and reliable in minimizing earthquake impacts on water utilities. To maximize the use of these procedures, the water system evaluation and planning steps must be thoroughly and effectively implemented. For this reason, emphasis in this report has been placed on water lifeline system evaluation, planning and program implementation.

Report Organization

The intent of this report is to provide a methodology for the evaluation of the seismic vulnerability of existing water lifeline systems and to provide retrofitting procedures tht may be implemented to minimize these impacts. It is intended for the use of water utility managers, engineers and municipal authorities in evaluating the needs of their systems. To this end the report has been organized in a "manual" format to aid in its application.

Chapter II provides a brief backgorund of earthquakes; their causes, manifestations and measurement. The purpose of this chapter is to provide fundamental information to the reader unfamiliar with earthquakes. Chapter III describes the methodology for identifying critical components of a water supply system. Chapter IV details the impacts of seismic forces on water supply components and describes how to use this information in developing a vulnerability analyses for critical equipment. Chapter V illustrates retrofit techniques that are applicable to a large range of equipment types identified with water supply systems. Chapter VI provides a discussion of the factors involved in developing a cost analysis of a retrofitting program including concerns about utilizing cost/benefit evaluations. Information is provided in enough detail to be of general use throughout the United States, however, areas with unusually high frequencies of strong earthquakes should supplement this information with appropriate local code requirements and guidance from seismic design experts.

Chapter II

Earthquakes in the United States

Purpose

The purpose of this chapter is to provide background information on earthquakes; their causes, frequency and potential for causing damage in the United States. This information is intended as an introduction to the subject to those unfamiliar with seismic phenomena. The information contained herein is only a cursory review of these subjects. If seismic analysis is anticipated, additional information from earthquake textbooks and professional scientists and/or engineer specializing in earthquakes should be consulted to assure competent handling of the program.

Earthquake engineering and research is a specialized, highly technical subject. It is a developing technology with many yet unanswered questions. Our understanding of seismic activity is based upon human experience and more recently intricate instrumentation. In the United States recorded human experience is at best only 200-300 years old, which is a relatively short term in which to develop seismic trends with respect to earthquake locations and related frequencies. The collection of seismographic information from strategically located stations in the U.S. has only been occurring on a significant scale for the past two decades. This program has been boosted by increased public and governmental interest in earthquakes and their potential impacts on society. The interest in this field has also been heightened by the rapidly advancing field of seismology which is increasing the usefulness of such data. This chapter attempts to introduce the reader to many of these areas in order to develop an appreciation for the complexities of seismic analysis in addition to providing background information essential for evaluating earthquake impacts on water lifelines.

Causes of Earthquakes

Earthquakes are caused by movements of the earth's crust over time. The crust is divided into a number of tectonic plates, which are continually moved by convection currents in the earths dense liquid magma. As movement between plates occurs, the material in contact can deform plastically with no sudden release of energy, this is known as "creep". Alternatively, stress can build up to the point that the plate material yeilds resulting in a sudden release of energy and displacement of one section with respect to another. Ground displacement is often caused by the sudden shearing action along this plane of intersection known as a "fault". The most devastating earthquakes occur along these plate boundaries. In the process of breaking or faulting between plates, vibrations are set up that are referred to as earthquakes. Some of the vibrations are of very low frequency, with many seconds between swings, where other vibrations are of high frequency, often to the point of being audible by man.

The vibrations are also of two basic types, compression waves and transverse or shear waves. Inasmuch as the compression waves travel faster through the earth, they arrive first at a distant point, and thus are known as primary or "P" waves. The transverse waves arrive later and are referred to as secondary or "S" waves. If one were to experience a strong earthquake the P wave would be the initial shock wave and the S waves a few seconds later would cause a swaying or rolling motion.

The geometric center of movement between these plates is called the hypocenter or focus. The geographical location of the center of movement if the ground surface above the focus is called the epicenter. The depth of the focus for any particular earthquake can be relatively shallow, as found in many western areas of the U.S. or they can be very deep, more characteristic of eastern areas of the U.S. This difference in focal depth has been indicated as being responsible for the relatively low areal impact of Western earthquakes (localized) as compared to the extensive involvement of geographic areas in eastern earthquakes. The western areas however suffers more extensive damage due to the presence of more faults and the areas impacted are generally closer to these fault lines, which are areas absorbing the most released energy.

Earthquake motions are irregular and each event, even in the same area will have unique characteristics. However, similarities have lead to the grouping of earthquakes into four different groups based upon common characteristic ground motions (2) as follows:

1. Practically a single shock - motions of this type occur only at short distances from the epicenter, only on firm ground, and only for shallow earthquakes.

2. Moderately long, extremely irregular motion - It is associated with moderate distances from the focus and occurs only on firm ground.

3. Long ground motion exhibiting pronounced prevailing periods of vibration - These motions are a result of the filtering of the previous types of earthquakes through layers of soft soil within the range of linear or almost linear soil behavior and from the successive wave reflections at the interfaces of these mantles.

4. Ground motion involving large-scale, permanent deformations of the ground - Specific sites may suffer slides or soil liquefaction.

It is convenient to group earthquake motions in this manner as a means of generalizing for both conceptual and design purposes. These generalizations are for convenience only, since ground motions with characteristics intermediate to those listed certainly occur.

Differential ground movements, such as landslides, settlements and surface fault breaks common in type (3) and (4) earthquakes have resulted in extensive property damage in the U.S. Severe damage resulting from huge landslides occurred in the 1964 Anchorage Alaska earthquake, while liquifaction and settlement were involved in much of the 1971 San Fernando earthquake.

Measurement

As previously indicated, the historic record of earthquakes consists of descriptions by persons impacted by earthquakes. Prior to recent technological advances, there were no instruments available for measuring the forces released by earthquakes. The problem with measuring earthquakes by interpretation of their effects on man is that this is a relatively subjective approach. However, for "historic" earthquakes this is the only record available.

The limits of the area of perception of an earthquake are often very difficult to define exactly. The area over which direct human observations can be made varies widely according to the energy developed at the focus of the earthquake and according to the focal depth. In addition, the interpretation of individual descriptions of earthquakes can differ based upon the individual acuity of the senses of different observers as well as the type of soil and surroundings in which the observer is located.

With the noted limitations, the average intensity of earthquakes are useful in measuring the damages to which seismic activities pose to man and his works. Efforts have therefore been made to establish a scale of intensity which is accessible to everyone, applicable everywhere, and which enables an observer without equipment to indicate easily the intensity of an earthquake at the point of observation. In the United States the scale used that meets these requirements is the modified Mercalli Scale (see Table II-1).

TABLE II-1

MODIFIED MERCALLI INTENSITY SCALE

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floor of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows and doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well built ordinary structures; considerably in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving automobiles.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving automobiles distrurbed.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in gound. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

The modified Mercalli Scale (MM) ranges from I, ground motion not felt by anyone, to XII, total damge. The MM number is a shorthand description of the effect of the ground shaking (3). Earthquake resistant design is usually built to resist intensities of MM VI - X, below this level only slight disturbances are noticable and beyond this level damage is so extensive that it is unrealistic to expect facilities such as water supply systems to function.

With the advent of instrumentation, specifically the seismograph, it became possible to quantitatively describe the magnitude of earthquakes. In 1935, C.F. Richter developed a magnitude scale for measuring earthquakes known as the Richter scale. The Richter magnitude represents the log of the amount of energy released during an earthquake. Each increase of 1 on the open-ended Richter scale represents a 10 fold increase in the amount of energy released. Earthquakes of magnitude 5.0 or greater generate ground motions sufficiently severe to be potentially damaging to structures (4). The largest know Richter magnitude even experienced was estimated at 9.0 in Lisbon in 1775. The Richter scale is not however a measure of damage as is the Modified Mercalli intensity scale, since it is only a measure of the energy released from earthquakes. Variations in the focal depth, location, soil compaction, etc. will result in earthquakes of similar magnitude to have vastly different impacts on man and the environment. Table II-2 illustrates this difference in its display of significant U.S. earthquakes.

The localized measurement of ground motion is recorded by strong motion accelerographs. These instruments record the horizontal and vertical components of ground acceleration in terms of percent of gravity (%g). These

TABLE II-2

A Selection of Significant U.S. Earthquakes*

Year	Date	Location	Mag.	Int.	Remarks
1663	Feb. 5	St. Lawrence River region		X	Rockslides near Three Rivers, Quebec, Chimneys fell in Massachusetts Bay region
1732	Sep. 16	St. Lawrence River region		IX	A large event
1755	Nov. 18	Off Cape Ann Massachusetts	6.0	VIII	Chimneys fell and buildings damaged in Boston and elsewhere. Many ships at sea were jolted.
1811	Dec. 16		7.5	XII	Sequence of three large earthquakes. Caused major changes in topography.
1812	Jan. 23	New Madrid, Missouri	7.3	XII	Affected two million square miles. Felt in Boston. 1.100 miles away. Because of
1812	Feb. 7		7.8	XII	remote location, only a few deaths.
1852	Nov. 9	Fort Yuma, Arizona		IX	Ground fissures. Many aftershocks.
1857	Jan. 9	Fort Tejon, California	8.3	XI	San Andreas fault offset 30 or 40 ft. fault ruptured for 250 miles. Because of remote location, only one known death.
1868	Apr. 2	Island of Hawaii	7.7	X	Volcanic earthquake on south slope of Mauna Loa. Much damage tohouses. Tsnami killed 46 people.
1868	Oct. 21	Hayward, California	7.5	IX	Extensive surface rupture on Hayward fault. 30 deaths. Many aftershocks.

*Source: Reference 5

TABLE II-2 (continued)

Year	Date	Location	Mag.	Int.	Remarks
1872	Mar. 26	Owens Valley, California	8.5	XI	One of the strongest U.S. earthquakes. Fault scarp 20 ft high, 27 deaths.
1886	Aug. 31	Charleston, South Carolina	7.0	X	Greatest earthquake in eastern United States. Several aftershocks. Much building damage. 110 deaths.
1895	Oct. 31	Charleston Missouri		VIII	Chimneys fell. Earthquake felt from Canada to Louisiana.
1899	Sep. 3	Alaska: near Cape Yakataga	8.3	XI	Ground uplifts; seiches; people unable to stand.
1906	Apr. 18	San Francisco, California	8.3	XI	San Andreas fault ruptured for 270 miles. Ground offset 21 ft. About 700 deaths during earthquake and fire.
1915	Oct. 2	Pleasant Valley Nevada	7.6	X	Large fault displacements in an unpopulated region. Adobe houses destroyed.
1921	Sep. 29	Eisinore, Utah		VIII	Chimneys toppled. Many aftershocks.
1925	Feb. 28	St. Lawrence River region	7.0	VIII	Felt over a wide area, south to Virginia and west to the Mississippi River. Little damage.
1925	June 27	Manhattan, Montana	6.7	VIII	Buildings damaged. Rockslides.
1925	June 29	Santa Barbara, California	6.3	IX	Much building damage. Sheffield Dam failed. 13 deaths.
1931	Aug. 16	Valentine, Texas	6.4	VIII	Buildings damaged: chimneys fell.

TABLE II-2 (continued)

Year	Date	Location	Mag.	Int.	Remarks
1932	Dec. 20	Cedar Mountain Nevada	7.3	X	Region was uninhabited at the time. Many ground fissures.
1933	Mar. 10	Long Beach, California	6.3	IX	Much damage to buildings, especially schools. 120 deaths.
1934	Jan. 30	Excelsior Mountains, Nevada	6.5	VIII	Minor surface faulting. Minor damage in Mina.
1934	Mar. 12	Kosmo, Utah	6.6	VIII	Many ground chnages (fissures, rockslides, new springs). Chimneys fell: 2 deaths.
1935	Oct. 18	Helena, Montana	6.2	VIII	Many buildings damaged: 2 deaths. Strong aftershock on Oct. 31 (magnitude 6.0) caused 2 additional deaths.
1940	May 18	El Centro, California	7.1	X	Large ground displacements along Imperial fault. Much building damage. 9 deaths. First important accelerogram for engineering use.
1949	Apr. 13	Olympia, Washington	7.3	VIII	Many buildings damaged. 3 deaths.
1952	July 21	Kern County, California	7.7	XI	Railroad tunnel collapsed: buildings damaged at Tehacharpi. Many large aftershocks. 12 deaths.
1954	July 6	Fallon, Nevada	6.6	IX	Damage to canals and roads east of Fallon. Minor building damage.
1954	Aug. 23	Fallon, Nevada	6.8	IX	Surface ruptures east of Fallon.

TABLE II-2 (continued)

Year	Date	Location	Mag.	Int.	Remarks
1954	Dec. 16	Fairview Peak, Nevada	7.1	X	Large fault scarps. Because of remote location, no deaths. Reservoir in Sacramento, 185 miles away, badly damaged by sloshing water.
1954	Dec. 16	Dixie Valley, Nevada	6.8	X	This earthquake occurred four minutes after preceding one: location was 40 miles north.
1958	July 9	Lituya Bay, Alaska	7.9	XI	Earthquake on Fairweather fault. Massive landslide created a huge water wave. 5 deaths.
1959	Aug. 17	Hebgen Lake, Montana	7.1	X	Huge landslide damaged Madison River and formed "Earthquake Lake." Large seiche in Hebgen Lake. Houses and roads damaged. Many aftershocks, 28 deaths.
1964	Mar. 27	Prince William Sound, Alaska	8.4	XI	Known as the Good Friday earthquake. Severe damage to Anchorage and many other cities. Landslides. Great tsunami damaged many coastal cities in Alaska and killed 11 people in Crescent City, California. 131 deaths.
1965	Apr. 29	Puget Sound, Washington	6.6	VIII	Buildings damaged in Seattle, Tacoma, and vicinity. 6 deaths.
1966	June 27	Parkfield, California	5.5	VII	Large ground accelerations (0.5 g).
1968	Apr. 8	Borrego Mountain, California	6.5	VII	One Coyote Creek fault. Surface fractures. Undeveloped area: minor damage.

TABLE II-2 (continued)

Year	Date	Location	Mag.	Int.	Remarks
1971	Feb. 9	San Fernando, California	6.5	XI	Several buildings and highway bridges collapsed. Many instrumental records obtained. 58 deaths.
1975	Mar. 28	Malad City Idaho	6.1	VIII	Minor damage to buildings.
1975	June 30	Yellowstone National Park Wyoming	6.4	VII	Rockfalls, new geysers formed.
1975	Nov. 29	Island of Hawaii	7.2	VIII	Volcanic earthquake near Kalapana (on south coast). Much building damage. Landslides, Tsunami caused damage along coast. Two deaths.
1978	Aug. 13	Santa Barbara, California	5.7	VIII	Extensive building damage; trains derailed.
1979	Oct. 15	Imperial Valley, California	6.7	VII	Extensive surface rupture on Imperial fault. Damage to buildings and canals.
1980	May 18	Mount St. Helens, Washington	5.2		Volcanic earthquake. Preceeded a major eruption that killed 60 people.
1980	July 27	Northern Kentucky	5.3	VII	Minor building damage.
1980	Nov. 8	Eureka, California	7.4	VII	Off the coast. Highway bridge collapsed; moderate building damage. Five people injured.
1982	Jan. 18	Franklin, New Hampshire	4.8	VI	Felt throughout New England.
1982	Jan. 20	Naylor, Arkansas	4.5	V	Many small earthquakes during a two-week period. (Naylor is 28 miles north of Little Rock).

measurements have great engineering application since knowledge of ground motion is essential for evaluating the behavior of structures during earthquakes.

To date there is a relatively limited data base of recorded ground accelerations of destructive earthquakes. However scientist and engineers have been able to extropolate from this data idealized models of ground motion relative to earthquake magnitude and location of faults. Housner (4) has presented an idealized intensity distribution along a fault line as indicated in Table II-3.

Housner also points out that these idealized models of ground motion are based upon typical conditions and do not take into account such special conditions such as vibrations or lurching of very soft soils, landslides, gross movement of rocks, etc. The following factors have been identified as influencing surface ground motions:

1. The nature of the source mechanism, the dimensions and orientation of the slipped area of fault, the stress drop, the nature of the fault movement, its amplitude, direction, time and history.

2. The travel path of the seismic waves, the physical properties of the rock, discontinuties, layering, etc.

3. Local geology, physical properties of soil layers and sedimentary rock, vertical and horizontal dimensions of bodies of soils and rock, orientations of bedding planes, etc.

TABLE II-3

Area in 1000 mi^2 Covered by

Ground Acceleration (%g)*

	M						
Acceleration	5.0	5.5	6.0	6.5	7.0	7.5	8.0
5	0.4	1.6	3.6	6.8	13	28	56
10		0.6	1.6	3.6	7.6	14	32
15			0.6	2.0	4.4	9.6	21
20				0.9	2.5	6.0	14
25					1.3	4.0	10
30					0.25	2.0	6.4
35						0.6	4.0
40							1.2

*Source: Reference 4

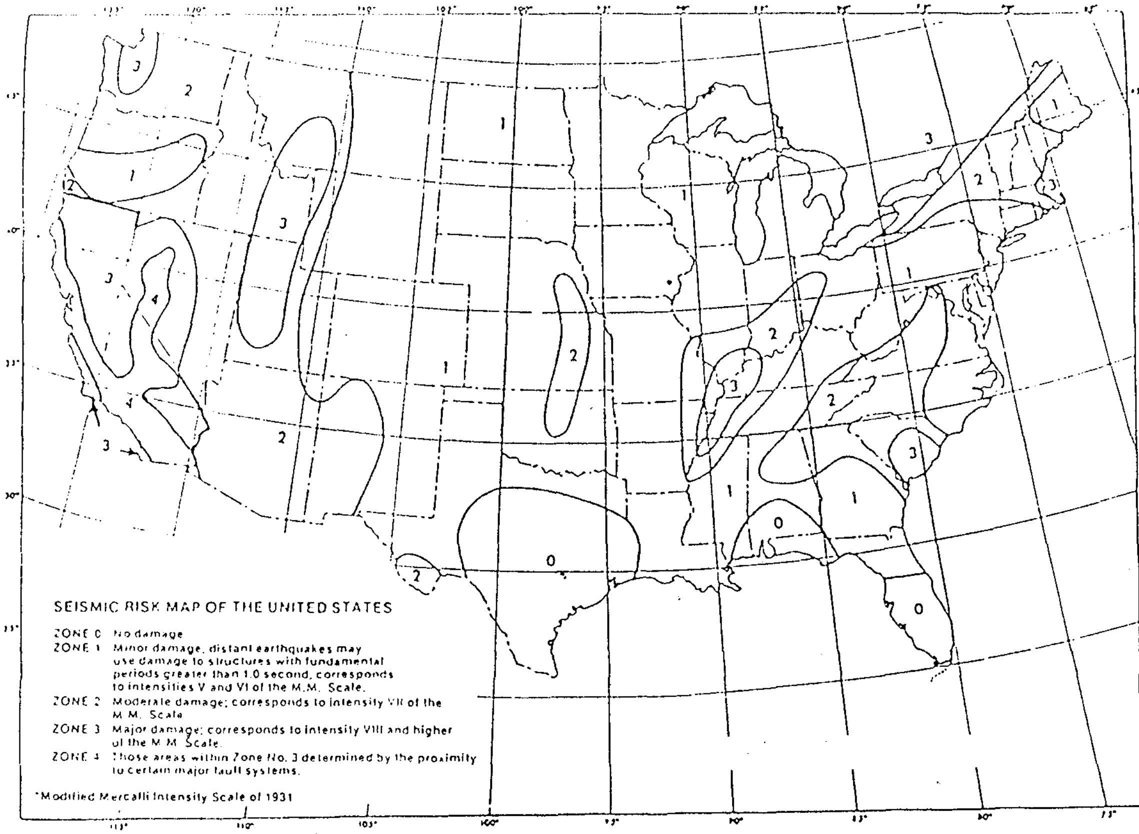
These special conditions or site specific conditions help to explain variations in the response of soils and hence the structures built on them to seismic forces. However it must also be kept in mind that for buildings and appurtenant items of construction and materials also have a great influence of structural response to earthquakes. This presentation attempts to describe only the natural physical phenomenon associated with earthquakes, thereby providing a background for further development of principles of earthquake engineering to water lifeline systems.

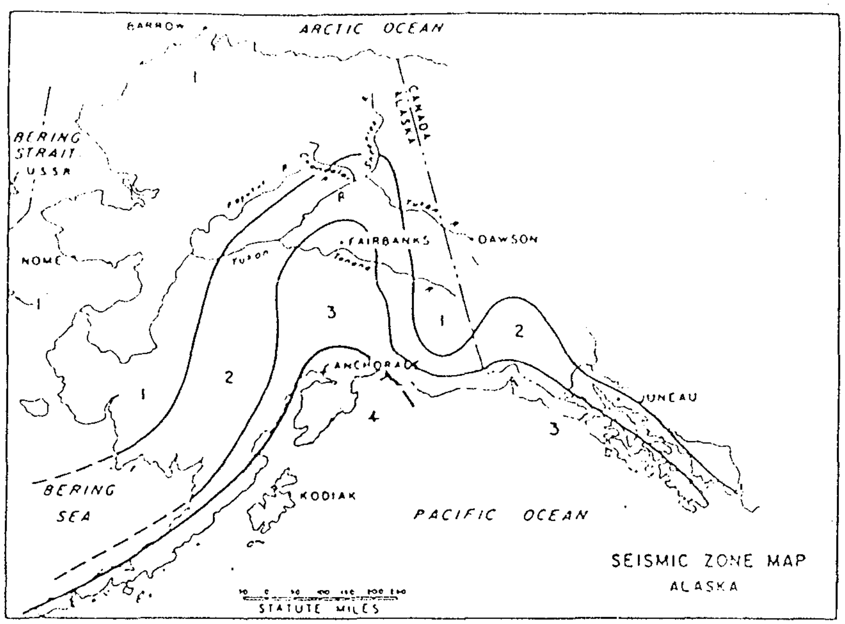
Seismicity

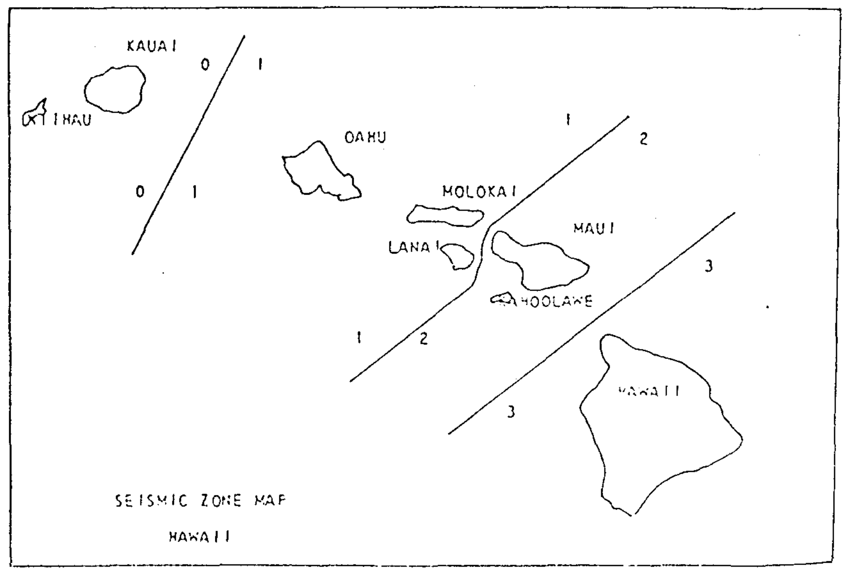
The areas of the United States that are subject to damaging earthquakes and the frequency of these natural disasters has been the subject of much research. The recognition that certain areas of the country are more subject to earthquake hazard than others has led to the development of seismic risk maps. One of the earliest works of this type was developed by S. T. Algermissen (6). The map of the continuous U.S. was based on the known distribution of damaging earthquakes and the modified Mercalli intensity associated with the earthquakes, strain release and consideration of major geologic structure and provisions believed to be associated with earthquake activity. The map was subsequently modified to include all 50 states and expanded from four to five seismic risk zones (0-4). Figure II-1 illustrates this map as adopted by the Uniform Building Code (7), Tri Service Manual (8), and other seismic design codes. These maps do not take into account the frequency of occurance of damaging earthquakes. The state-of-the-art does not allow for this type of map to be developed. The historical record of reoccurance rates is too incomplete to accurately depict this type of information.

Figure II-1

Seismic Zone Maps of The United States







Since it is not possible to predict the size, location and time of damaging earthquakes precisely, and since the data on occurances of earthquakes are incomplete, hazard assessments must rely heavily on probabilistic statements about the likelihood of future earthquakes and ground shaking. These assessments have a major influence on the need and the feasibility of implementing aseismic retrofit programs and therefore is discussed in more detail in subsequent sections of this report.

There are a number of reasons for evaluating the vulnerability of water supply facilities. The critical need for water for maintaining public health and fire fighting needs are primary reasons. The water supply system review process will stimulate system managers to thinking about the risks of earthquakes and the impact they can have on this essential lifeline. Incredibly, many utility managers and owners in areas subject to moderate earthquakes have not reviewed their systems or developed emergency response programs. Most water supply systems were built prior to the 1976 Uniform Building Code which contained the first discussion of essential facilities. Seismic resistant design for non-structural (mechanical and electrical) systems was not addressed until 1978 in the Tentative Provisions for the Development of Seismic Regulations for Buildings (ATC-3) (9). Even to the present time, the adoption of these codes and provisions in the water lifeline industry has not taken place. This situation indicates that most of their non-structural equipment is probably not even treated with the minimum seismic consideration. Many items are not anchored and most have never received any form of dynamic consideration. These facilities are therefore very likely to fail if significant seismic forces (i.e., MMI 5) occur during the useful life of the facilities.

Chapter III

Critical Water Supply Components

Background

Under normal operating conditions a properly designed and operational public water supply system is capable of meeting water supply needs for drinking, cooking, personal hygiene, fire fighting, commercial/industrial needs and numerous related activities. Generally these requirements are met by water production of approximately 100 gallon per day per capita in the service area, plus storage requirements for peak demand and fire fighting. In addition, this quantity of water must be of sufficient quality to meet public health and aesthetic requirements (taste, odor and color) as well as being at sufficient pressure to meet the demands of system users.

The management of a water utility is a complex operation encompassing a multitude of programs, all directed toward guaranteeing a continuous, uninterupted supply of high-quality water for the uses outlined above. U.S. water utilities have an exemplary record of maintaining quality and quantity in water supplies under the most adverse conditions. Nevertheless, it is recognized that disruptions in water supply do occur and quality impairment has been recorded in many parts of the United States.

It has only been recently that concern has been expressed relative to the impact earthquakes can have on public water supply systems. This concern has been fostered by several moderate to major earthquakes in California when water systems have suffered various levels of damage. In addition, secondary earthquake damage (i.e., fire) and prolonged recovery periods due in part to the lack of sufficient water supply have been experienced. Post earthquake event inspections of these damaged facilities has provided a data base on equipment damage and failure modes most frequently responsible for system failure. Table summarizes this information from some of the more recent, extensively evaluated water system impacts due to earthquakes.

Performance Goals

It is not considered technically or economically feasible to design or retrofit water supply systems to sustain earthquakes of major magnitude without experiencing any damage. Therefore it becomes evident that a planning process must be developed to identify water system performance standards capable of achieving an established level of performance determined to be the minimum acceptable for post earthquake needs. Minimum acceptance performance goals are based upon needs to protect human lives and public health. If it can be determined that it is economically and technically feasible to retrofit a facility to meet these minimum requirements, additional retrofitting management priorities and the cost/benefit of the additional system protection.

The level of retrofitting required is dependent on the level of risk that the utility management and owners are willing to accept. The level of risk is a parameter defined by the following factors:

1) The intensity of future earthquakes
2) The return frequency of future earthquakes
3) The vulnerability of the water supply system to earthquake damage and,
4) The vulnerability of the population to hazards associated with an inadequate water supply after an earthquake.

The minimum acceptable performance standards of a water supply system are related to item number four, above. The threat of fire and disease due to inadequate public water supplies has been substantial after many major earthquakes both in the U.S. and abroad. Fire has caused extensive damage after the 1906 San Fransisco earthquake, and the 1923 Tokyo, Japan earthquake. Modern construction and enforcement of fire codes has helped to minimize this threat in modern cities. However, the presence of old sections in many of todays cities and the numerous fire outbreaks associated with 1970 San Fernando, California earthquake (approx. 145) indicate this hazard can be substantial.

Public health is threatened any time there is not a safe supply of water required for consumption and sanitation purposes. Though recent earthquakes in this country have not been associated with disease outbreaks due mostly to the quick response of the National Guard and the American Red Cross in supplying tank trucks of purified water, the potential for this hazard is still present.

In addition, recovery efforts are severely hindered if a source of clean water is not available. The potential for broken sewer lines and inadequate sanitary facilities also increases the hazard of disease developing after a major earthquake. Therefore, in many cities the minimum performance requirements will be: 1) to provide a source of safe drinking water and 2) provide for fire fighting in areas where greatest fire hazard exists.

Drinking water for emergency purposes does not require the quality or quantity of water required of a normally functioning system. In turbid water supplies immediately following a major earthquake it may be necessary to increase chlorine concentrations in the distribution system from 2 to 5 ppm in efforts to ensure the water is not capable of transmitting disease if it has been contaminated. The quantity of water required for drinking and cooking has been estimated at only 5 gallons per capita per day. Therefore estimates of the water supply needs for drinking and cooking for the immediate post earthquake period (first 24 to 48 hours) are modest and require only a small percentage of the water system to be functional.

However, fire fighting needs can not be as easily evaluated. The location of fires and the quantity of water required to control them is not readily predictable. In addition, fire flow often requires maximum utilization of the system capabilities, especially of the distribution and storage facilities to meet the high volume and pressure requirements for putting out fires.

Ultimately water requirements after a devastating earthquake can be assumed or estimated only in terms of the magnitude of the disaster and the capabilities of the system itself.

Based upon the above discussions, the following operating goals are recommended. They are concerned primarily with the immediate post earthquake water requirements of an urban area with the assumption that recovery operations will begin shortly after this period.

a. Primary goals during the immediate emergency period

   1. Continuous hydraulic flow through or around water treatment facility
   2. Provide a disinfection for public health
   3. Maintain integrity of arterial water mains and associated storage facilities
   4. Provide for safety of water utlity personnel

Means of achieving these goals will be dependent on the specific conditions associated with any given water supply. However the treatment, distribution and storage of water supplies can be generalized to aid in the evaluation of "typical" water lifelines since the basic systems and subsystems of water lifelines consist of comparable functional units as follows:

Typical Systems	Typical Subsystems	Components
Raw water intake	Intake tower	Pipeline, intake structure valves
Transmission facilities	Pumping stations pipelines	Pumps and motors emergency power control panels
Treatment facilities	Headworks coagulation settling filtration disinfection	Pump and motors tanks, chemical feed equipment, pipes, control panels

Distribution facilities	Pump stations pipelines	Pipes, valves pumps and motors emergency power
Storage facilities	Elevated tanks ground level tanks control facilities	Pipes, tanks valves

This list is only for example purposes to illustate the commonality between water systems, without regard to specifics of design, location or age. This general approach will be used in developing a functional analysis of water system to identify those systems, subsystems and components whose function is required (critical) for meeting the system performance goals during the emergency operating period following a moderate to major earthquake. After identification of the critical components of a water system, evaluations of vulnerability of these components will be reviewed to determine retrofit priorities within a water supply system. The actual level or extent of retrofitting will of course be dependent or loacl seismicity (frequency and intensity), acceptable risk levels and available resources.

Critical Systems

Once the minimum emergency performance goals have identified it is necessary to review those systems and subsystems of the water supply facilities to identify those that are required to function to meet the established goals. This is done by conceptually skelatonizing the facilities into critical systems and subsystems according to each requirement as follows:

Potable Drinking Water (quantity to meet 24-48 hr needs*)

Critical Systems	Subsystems
Raw water intake	intake structure, submersed pipes
emergency power	generator and distribution facilities
transmission	pump station, buried pipes, flow control,
sedimentation	tanks
disinfection	chlorination facilities, clorine storage
isolation and by-pass systems	buried and surface pipes, flow control
finish water storage	tanks,
distribution	pump station, buried pipes

*estimated at 5-25 gpcd

Fire Fighting Capability

Critical systems	Subsystems
Raw water intake	Intake structure, submerged pipes
Emergency power	Generation and distribution facilities
Transmission	pump station, buried pipes, flow control
Isolation and bypass systems	buried and surface pipes, flow control
Finish water storage	tanks
Distribution	pump station, pipes, valves
Distribution storage	buried, ground level and elevated tanks

The systems itemized are considered to be the specific functional units of the water supply system that must be operational after an earthquake. The level of function (i.e. 10%, 50%, etc) will depend upon the required specific performance goals established for emergency conditions. The subsystems are unit operations within each of the systems (e.g., pump stations, tanks, etc.). Similar subsystems often exist between the various systems of a water lifeline as indicated above. There may exist other critical systems or subsystems not considered here if there are significant differences in the water system design or emergency performance goals exceeding those proposed for this evaluation. The list developed in this text is sufficient for most conventional surface water supply systems.

For each of these systems and subsystems to be operational it is necessary that the components of these functional units (i.e., equipment) be intact and operational. Within each critical subsystem are numerous critical equipment items as well as support equipment. This equipment is often referred to as non-structural equipment (i.e., not an integral part of the building structure) and consists of mostly electrical and mechanical items. For retrofitting purposes individual equipment items will be defined as functional units of the subsystems. The evaluation of individual components of these equipment items is beyond the scope of the project and is better addressed by equipment manufacturers. A list of typical equipment found in some of the critical subsystems of water supply systems are listed in Table III-1.

Table III-1

Typical Equipment at Water Supply Facilities

Subsystem	Equipment
Pump station	pumps, motors, lights, control panels, emergency power supplies (batteries), pipes, valves, meters, switch gear, crane, air compressors
Emergency power generation	motor-generator assembly, control panel, day tank, ventilation fans, light fixtures, etc.
Chlorination facilities	chlorinators, evaporators, water pipelines, ventilation fans, seals, crane, chlorine analysers, etc.
Pipeline systems	pipes, valves, couplings
Flow control	meters, control panels
Sedimentation tanks	concrete tanks, pipes, valves, sludge scrapper and drive, sludge pumps, etc.
Power substations	transformers, control panels
Chemical storage	storage tanks, storage racks, trolley hoist, weighing scale
Waste storage tank	tank, valves piping, level recorder or telemeters device, etc.

A water lifeline functional analysis has previously been developed by EQSI (1) and is presented in Table III-2 as a guide for evaluation of other systems. This analysis of essential water supply functions and critical equipment provides a logical sequence for evaluation of water supply systems. The purpose of a functional analysis is to identify essential functions and the equipment required for the operation of these functions. It also serves as a guide for evaluating a water supply system to limit damage, inconvenience and downtime, not necessarily prevent it.

The application of a functional analysis to a water supply system requires a detailed review and evaluation by personal knowledgable about the specific facility in question and water system operation in general. Often a particular function in a water treatment facility can be achieved in a variety of ways (alternate pathways) by rerouting flow or utilization of parallel unit operations.

Due to the limited scope of this project, essential functions associated with structural integrity of buildings housing essential equipment will not be addressed. Obviously the goals of any post earthquake emergency response plan requires that these buildings remain intact. The evaluation of these structures and their foundation should be evaluated according to well established principles and guidelines of building analysis (10, 11, 9, etc.). If essential buildings such as control centers, maintenance facilities or other buildings housing equipment required for post earthquake system operation are found to be inadequate, decisions will need to be made concerning the feasibility of relocating essential facilities, retrofitting the existing facilities or building new seismic resistant structures.

TABLE III-2 FUNCTIONAL ANALYSIS OF WATER TREATMENT WITH LISTING AND DESCRIPTION OF ASSOCIATED PROCESS EQUIPMENT (1)*

Function	Subfunction	Process equipment	Location	Relation to other elements	Required availability rating
Receive raw water					1 or 2
	Receive raw water from transmission pipelines	Influent pipes, valves	A	IV	1 or 2
	Establish hydraulic head	Influent well	A	II	1 or 2
	Provide for plant bypass	Bypass chamber	A	II	1 or 2
		Bypass piping and valves	A	IV	1 or 2
	Convey water to next operation	Pipes and valves	A	IV	1 or 2
	Monitor flow	Flow meter and recorder	D	II	1 or 2
Remove volatile and oxidizable impurities					
	Receive influent flow	Raw water channels or pipes	A	IV	1 or 2
	Contain flow and provide turbulence	Aeration tank	A or B	II	1 or 2
		Filters (air	B	II	7
		Air compressors	B	III	7
		Air meters	B or D	III	7
		Piping (air)	B	IV	7
		Diffusers	B or D	II	7
	Convey for further treatment	Piping and valves	A	IV	1 or 2
Remove colloidial and settleable impurities					
	Receive influent flow	Piping and valves (raw water channels)	A	IV	1 or 2
	Provide chemicals	Aluminum sulfate: hopper care, drums, paper bags	B or C	I	5 or 6
		Storage bins (with vibrators)	C	I	5 or 6
		Dry-feed machines	B	I	5 or 6
		Piping	D	IV	5 or 6

TABLE III-2 (continued)

Function	Subfunction	Process equipment	Location	Relation to other elements	Required availability rating
Remove colloidial and settleable impurities (continued)					
	Provide for mixing	Mixing tank	A	II	1 or 2
		Mixer	D	I or III	5 or 6
	Contain chemically treated water	Flocculation-sedimentation basin	A	II	1 or 2
		Flocculating baffles	D	III	5 or 6
	Collect and convey settled water for further treatment	Overflow wiers and effluent channels	D	III	1 or 2
		Piping and valves	A	IV	1 or 2
	Collect and convey settled solids	Sludge scraper and drive	D	III	5 or 6
		Sludge pumps	B	II	5 or 6
		Sludge control valves and piping	A or B	IV	5 or 6
		Meter (sludge)	D	II or III	7
Remove filterable impurities					
	Receive settled water	Pipes, valves and fittings	A or B	IV	1 or 2
	Contain settled water and provide filtration	Filtration tank	A, B or C	II	1 or 2
		Distribution pipes	D	IV	1 or 2
		Valves and motors	B	III	1 or 2
		Filter media	D	III	5 or 6
		Rate controllers	D	III	5 or 6
		Flow meter	D	III	7
		Underdrains	D	III	1 or 2
	Collect filtered water	Flow collection chamber	D	III	1 or 2
	Monitor filter condition	Head loss meter	D	III	5 or 6
	Collect filtered solids	Washwater pipe and valves	D	IV	5 or 6
		Backwash water trough	D	III	5 or 6
		Surface wash pipe and sweep mechanism	D	II	7
	Convey filtered water	Filtered water pipe and valves	D	IV	1 or 2
	Convey filtered solids	Drain pipes and valves	D	IV	5 or 6

TABLE III-2 (continued)

Function	Subfunction	Process equipment	Location	Relation to other elements	Required availability rating
Provide disinfection					
	Store chlorine				
	Provide for chlorine container storage	Storage racks	B	I	1 or 2
	Provide mobility of container	Trolley hoist	B or D	I	5 or 6
	Monitor supply on hand	Weighing scale	B	II	3
	Feed chlorine				
	Supply chlorine	Chlorine cylinders	B or C	II	1 or 2
		Chlorinators	B	II	1 or 2
	Control feed	Flow control valves and piping (chlorine)	D	IV	1 or 2
		Flow control valves and piping (water)	D	IV	1 or 2
	Monitor and record chlorine feed rate	Recorder	D	II	5 or 6
	Analyze wastes for chlorine residual	Chlorine residual analyzer and recorder	B or D	II	5 or 6
		Ambient chlorine detector	D	I	1 or 2
	Convey chlorine solution	Piping and valves	D	IV	1 or 2
		Protected water system (piping, tank and pump)	D	II and IV	1 or 2
	Provide contact				
	Receive effluent from preceding process	Pipe or channel	A or B	IV	1 or 2
	Contain flow	Contact tank	A or B	II	1 or 2
	Provide mixing	Chlorine diffuser	B or D	II or III	1 or 2
		Baffles	D	III	5
	Convey treated water	Disinfected water pipe	A	IV	1 or 2
	Meter or monitor flow	Meter	A,B or D	II	5

TABLE III-2 (continued)

Function	Subfunction	Process equipment	Location	Relation to other elements	Required availability rating
Prepare water for distribution					
	Receive flow	Pipes and valves	A	IV	1 or 2
	Provide storage	Finished water reservoir	A or B	II	1 or 2
	Remove and convey water for distribution	Finished water pumps and motors	B or D	II	1 or 2
		Pump motor controls	B or D	II	1 or 2
		Finished water piping and valves	A	IV	1 or 2
	Monitor flow	Flow meter and recorder	D	II	6
Dispose of process residence					5 or 6
	Dewater solids				
	Receive solids	Influent pipes	A or B	IV	5 or 6
	Contain solids	Thickening tank	A or B	II	5 or 6
		Piping and valves	A,B or D	IV	5 or 6
	Convey solids for further treatment or discharge	Piping and valves	A or B	IV	5 or 6

Explanation of symbols*

Location

A - Buried or in ground
B - Surface
C - Elevated
D - Building or structure supported

Relation

I - Isolated
II - Interconnected, but separate
III - Mechanically coupled, but separate
IV - Connecting piping

Availability Rating

1. Essential operations (continual)
2. continual operation preferable
3. short term make shift operation
4. short term shut down acceptable
5. long term make shift operation
6. intermediate shutdown acceptable
7. long term shut down acceptable

* See reference 1 for detailed explanation of terms.

In addition, the performance of distribution systems will not be addressed. Past performance of these systems has been shown to be highly site specific. Most distribution systems are very extensive and are spread out over relatively large geographic areas with a wide range of earthquake response characteristics. These conditions make it extremely complicated to predict earthquake response of distribution systems. The level of effort required to evaluate a distribution system and the cost of replacing or retrofitting the components makes this level of protection beyond reasonable consideration for most existing systems.

However the arterial mains leading from the finish water pumping station to distribution storage facilities and including these storage facilities is critical to the utilization of water during the post earthquake, emergency response period. A functioning water treatment plant is of little use if the potable water can not be sent to, or near, its point of need. In addition fire flows and pressure required to meet even moderate fire fighting needs depends on the availability of stored water. In areas where significant earthquake intensity can be expected to occur during the life of the arterial main system and storage tanks (100 yards) it will be necessary to evaluate their expected response and either provide retrofitting to identified vulnerable locations or parallel the existing system with seismically designed and stabilized components.

Target Areas

Urban areas are usually composed of districts, zones, and neighborhoods based upon common land use and density of development. These divisions are frequently composed of structures built during the same time period. The importance of this fact to our present topic regards the age and condition of the buildings and their associated utility systems. Modern building and fire codes may reduce the vulnerability of some buildings and utility lines to seismic damage and fire hazard. Older districts built under outdated standards of construction and questionable code enforcement may be highly vulnerable to seismic and fire hazards. In addition, these older sections are frequently very densely populated and contain corroded water distribution systems. These conditions tend to magnify the impact of seismic forces and threaten many more lives than more modern sections of the urban area.

If assumptions of these types are applicable within an urban area, it may be advantageous to identify these regions during the initial seismic evaluation program. The benefit this provides for the seismic retrofit program is to effectively reduce the amount of arterial main and storage system retrofitting to those areas that are the most vulnerable to earthquake hazards. Retrofitting or replacing essential water mains is very expensive and in many areas of the country it would not be economically feasible to uniformly retrofit an entire urban area. Other controlling factors in establishing regional vulnerability within an urban area can include; geology, soil types, proximity to faults, etc. If these can be identified it may be appropriate to spend limited resources in these areas or at least give these areas priority when an seismic program is initiated.

This type of planning approach also has merit with respect to post seismic event emergency response planning of which the water utility is an important part. Dividing the urban area into priority zones may allow for a more meaningful estimate of the quantity of water needed for emergency response. It may also indicate locations where valves should be placed with distribution system to prevent excessive water and pressure loss from priority areas, which generally would be defined as areas with the greatest potential threat to human lives.

New Installations

The cost or technical feasiliby of retrofitting an essential component of a water lifeline system may be impractical. This situation can occur if the critical item is excessively corroded, space for proper bracing is unavailable retrofitted unit can not meet minimum standards, or the cost of retrofitting exceeds the cost of an seismically designed new installation. In these instances new equipment and its installation should follow applicable seismic design codes. Often it will be advantageous to leave the former installation intact if possible, allowing a redundant or back-up system for future use if needed.

Before new equipment is purchased and installed, applicable local, and state codes regarding seismic design should be consulted as well as utilization of the services of design professional qualified in seismic design. It may be practical to establish specifications and performance requirements for seismic resistance before obtaining bids for the required new equipment. This could result in a higher level of protection and possibly reduce seismic installation costs. The feasibility of purchasing aseismically designed components depends on a variety of factors including; performance requirements, and the availability and cost of specially designed components. Theoretically, as more communities initiate aseismic retrofitting programs the availability of such items will increase and the unit cost will decrease.

Chapter IV

Water Lifeline Vulnerability

Background

The vulnerability of a water supply system to earthquake damage is the degree to which the operation of the system is adversely affected by the seismic event. A water supply system generally operates according to the rule of the "weakest link". That is to say that the operation of the system to meet the established performance goals is dependent on the successful operation of a sequence of critical systems, subsystems and components. The failure of any single essential item may jepordize the operation of the whole system. This is one of the reasons that redundant and/or parallel units are highly recommended. Operation flexibility in the water utility inherently reduces its vulnerability to ultimate failure.

Analysis and evaluation of vulnerability to seismic forces is an important part of the water lifelines emergency response capability. This analysis includes a determination of how the various essential components of the utility might be damaged and to what extent the functional operational capability would likely be impaired under various intensities of seismic events.

The vulnerability determinations consider the probable response of components of the system to various seismic impacts (ground failure, vibration, etc.) and relates this to the functional operation of the surviving system. In addition the indirect damage response must also be considered. For example, the effect of adjacent non-essential equipment items collapsing or otherwise damaging critical components. Secondary or indirect damage may jeporadize human safety and thereby restrict the ability of operations personnel to access critical areas of the water lifeline system; for example the collapse of non-essential electrical control panels may block access to critical facilities in a building as well as pose a hazard of possible electrocution if power control switches are not accessible.

The seismic response and vulnerability of equipment items are dependent on site conditions, equipment design and installation methods. The ground accelerations associated with seismic events and their characteristic vibrations can be either attenuated or magnified due to the characteristics of the specific location. The reliability of lifeline systems is dependent on their ability to resist these earthquake forces.

Site Vulnerability

The vulnerability of a particular site is dependent on several factors such as site geology, soil types, proximity to fault lines and the location and magnitude of potential earthquakes. Seismic hazard or site maps may be suitable for determining the general seismicity of an area but they are usually insufficient for evaluation of site vulnerability. Some areas of southern

California have had microzonation maps developed that are potentially very useful in evaluation of site vulnerability. However, the lack of seismic data for other areas of the county generally makes this level of evaluation impractical, requiring that detailed seismic, geologic and soils studies be conducted on a site specific basis.

Seismic effects that can potentially damage a water system have been identified as the the following (12):

1) Horizontal and vertical displacement or shearing on fault lines and tilting of fault blocks in the vicinity of faults.

2) Severe shaking within or adjacent to fault zones. Damage depend on the amplitude, frequency, and duration of shaking.

3) Liquification and settlement, or consolidation in areas of natural or manmade fill or alluvium.

4) Landslides in hilly areas.

Sites that have been determined to be in seismic areas of the U.S. (i.e., seismic zones 3 and 4) should evaluate the site vulnerability of their water supply systems with respect to these hazards. This generally requires that a geologiest familiar with the area, review the soil borings information for the original site development records and/or the taking of additional borings as necessary to identify the character and suseptability of the water treatment and distribution system to the types of hazards identified.

Equipment Vulnerability

The vulnerability of equipment to damage from seismic forces is dependent upon the intensity of the forces experienced by the equipment and the ability of the equipment to withstand these forces. Past studies of earthquake damage to water supply systems and other utilities in recent years indicates repeditive modes of damage. Underground components (i.e., pipelines, tanks, etc.) were mostly affected by differential ground movements, while above ground components (i.e., pump stations, control centers, etc.) were damaged by strong ground shaking. Therefore ground failure areas identified in the site evaluation are areas that damage can be expected to occur. Consequently they generally require priority remedial action if critical equipment has been identified in these ground failure areas. Where ground failure is not identified as being a likely consequence of earthquake activity, above ground equipment and associated structures should be evaluated according to its critical function and its vulnerability to ground shaking. the vulnerability of equipment to damage from ground shaking is dependent on the following factors:

1) For equipment located within buildings, the response of the building structure will influence equipment response. Building can potentially amplify impact of seismic forces on the equipment resulting in greater damage than would otherwise occur (i.e., equipment located in second story or higher areas).

2) Attachment to the structure, rigid anchoring generally minimizes equipment response.

3) Equipment characteristics related to configuration construction, weight etc. (e.g., tall, relatively light electrical panels are suseptible to overturning due to their high center of gravity.

4) Interrelationship between equipment items suseptible to differential movement.

5) Secondary damage or failure of equipment due to the seismic impact to other equipment (e.g., the failure of a motor may be due to failure of the power system or the collapse of an adjacent piece of equipment).

Isolated equipment is that which stands alone and is not structurally connected to any other equipment. An example would be a storage bin for chemicals. The second category refers to that equipment which is not mechanically or structurally coupled, yet is interconnected with other process elements by piping or other equipment. An example of mechanically coupled equipment is an air meter which is coupled to an air compressor. The last category refers to the piping (and valves) that connect various equipment items.

Since equipment of different size, configuration and installation can respond differently to the same earthquake forces, it is important to consider the interrelationships between equipment when evaluating potential damage. Variations in equipment responses to seismic forces can result in differential movement of interconnected equipment and/or lead to secondary damage of essential equipment. The typical interrelationships found at water supply facilities are as follows:

- o Isolated
- o Interconnected, but separate
- o Mechanically coupled, not separate
- o Connecting piping

Historical Damage

General

The interest in water lifeline earthquake engineering over the past two decades has lead to the publication of numerous reports on the extent and modes of damage experienced by water utilities from seismic forces. The detail of these reports has improved in recent years due to the interdisciplinary nature of investigating teams. Experts in structural, mechanical, sanitary and electrical engineering have combined their efforts to identify the modes of failure associated with water lifelines and other utility lifeline systems. These teams have investigated earthquakes throughout the world resulting in evaluations under various conditions and types of water lifelines. Earthquakes investigations that have lead to an expansion of the data base of seismic damage to water lifelines include the following earthquakes; 1972 Manazua, Nicaragua; 1978 Muyogiken-oki, Japan; 1964 Niigata, Japan, 1964 Anchorage, Alaska, and others.

The review of these reports indicates that the failure modes for non-structural equipment are often similar. This information can be used to "predict" the vulnerability of equipment in other water lifeline systems. Table

IV-1 is a summary of damage modes frequently associated with subsystems and components of water supply systems. In addition, Table IV-2 is a summary of the realtive degree and consequence of seismic damage to the essential service systems of water supply and related systems.

Intake Structures

Water intake structures, typically tower type structures located in water impoundments, are subject to failure from earthquake forces. The lateral inertia effect of the structure's mass and surrounding water may cause failure in shear at the base of the structure or in bending of the column. The foundations of these structures may be founded on unstable submerged strata vulnerable to displacement. Nearby landslides of unstable soil may damage these intake structures as well. In general, landslides from unstable, steep ground slopes are a major cause of earthquake induced damage to water intake structures as illustrated in the three examples below.

A landslide from an adjacent earth dam embankment caused outlet tower #1 in the Lower Van Norman reservoir (Los Angeles Department of Water and Power, LADWP) to topple during the 1971 San Fernando earthquake. Sand, gravel and rocks entered the distribution system through the broken intake, causing extensive damage to pumps, instrumentation and controls. Outlet tower #2 in that same reservoir experienced slight cracking. Both these towers, built in 1914-1915, were designed as unreinforced concrete gravity structures (13).

TABLE IV-1

SUMMARY OF COMMON DAMAGE MODES ASSOCIATED WITH SEISMIC IMPACT TO WATER LIFELINES

Subsystem	Components	Recorded Damage Modes
Inlet structure	Foundation	Subject to foundation/soil interface failure due to liquification and land slide
	Attached pipes	Damage due to compression/extension of joints; ruptured pipes allow entry of sand, gravel and rocks causing damage to intake pumps.
Wells	Motors	Failure due to loss of power, subject to differential movement that properly anchored.
	Well shaft and casing	Subject to shearing or being crushed due to soil displacment, also subject to bending due to lateral displacement of components
	Groundwater	Possible ground water hydrology disruption or pollution due to leaking sewers or septic tanks.
	Pipes	Attached pipes subject to damage from differential movement.
Water transmission lines	Large diameter pipes	Subject to large differential ground surface movements such as at fault crossings, also damage due to compression/extension of joints.

TABLE IV-1 (continued)

Subsystem	Components	Recorded Damage Modes
Pumping stations	Motors	Failure due to loss of power; also subject to damage due to ground shaking, especially if mounted on vibration isolators.
	Motor control centers and electrical panels	Subject to relay and switch chatter resulting in failure of associated systems. Ground shaking can cause cabinets to topple.
	Intake discharge piping	Differential movement has caused pipe failure at wall penetrations and pump attachments.
	Mechanical equipment interfaces (motor/pump, compressors, etc.)	Differential movement causes connecting system failures (piping, electrical conduit, shafts, etc.). Close proximity between equipment and/or walls can cause damage from vibration.
	Equipment (ground)	Support and anchor system failure due to motion of equipment, particularly if no positive base anchor system exists.
	Process piping	Failure of large diameter piping at elbows and bends; joint separations and hanger fractures.
Treatment facilities	Cloculator/Clarifiers	Sloshing water can cause horizontal tank movement or wall cracks or failure. Extensive damage of associated quipment such as center wells, baffles, etc. is common.
	Chemical feed system	Damage of equipment not properly anchored; mixers, pumps, tanks subject to shifting and falling. Chemical storage facilities subject to sloshing and/or toppling. Differential movement of components can cause failure of attached piping and feed systems.

TABLE IV-1 (continued)

Subsystem	Components	Recorded Damage Modes
Treatment facilities (continued)	Mechanical systems	Subject to anchor failure, differential movement and failure of electrical, piping or mechanical interfaces. Particular vulnerable to change if mounted on vibration isolators.
	Heavy tanks and boilers	Have shifted or toppled when supports or floor anchors failed.
	Electrical systems Electrical panels, transformers	Subject to vibration and differential movement. Also subject to shifting or toppling when support or anchors fail.
	Instrumentation and Control Consoles	Subject to vibration damage causing internal sub-components to dislodge, differential movement causing electrical cable connections to break.
Storage tanks	Surface mounted tanks	Sloshing water causes horizontal forces on tank walls causing tanks to slide, tip or cause bulge in tank walls; seams may burst due to extensive stress; foundation failure may cause tipping or overturning, may also result in shell or roof structure to buckle.
	Buried tanks	Differential movement at tank and correcting piping; similar failure as large pipelines including compresion/extension sources and shear forces on pipe/tank corrections.
	Elevated tanks	Failure due primarily to failure at tank support structure. High center of gravity responsible for tipping. Sloshing causes forces on tank walls similar to surface mounted tanks.

TABLE IV-1 (continued)

Subsystem	Components	Recorded Damage Modes
Emergency power	Motor/generator	Differential movement of sub components such as engine, generator, fuel line, exhaust piping, etc. can cause failure.
	Batteries	Damage due primarily to collapse of battery racks that inappropriately attached to building structure.
Communication system	Communication equipment	Subject to relay chatter and subcomponents being dislodged, etc. Shelf supported components subject to movement off shelf and falling.
Chlorination system	Chlorine cylinders	Unrestricted tanks subject to toppling or rolling causing possible tank rupture; differential movement of chlorinator/piping attachments can result in chlorine leaks. Scales can induce excessive vibration to tanks similar to vibration isolators resulting in change to scales and attached cylinder.
Distribution piping	Pipes and fittings	Numverous failure modes including soil failure, pullout or separation of joints, differential movement at junctions or connections with pipeline appurtenances which respresent discontinuities in pipeline structure; vibration induced damage, especially in corrosion weakened pipes. Particularly vulnerable in AC and gray-iron cast pipe. Large diameter pipes generally sustain less damage than small diameter pipes.

TABLE IV-2

RECORDED EARTHQUAKE DAMAGE TO ESSENTIAL SERVICE SYSTEMS*

Essential Service System	Relative Degree of Damage	Consequence of Damage	Most Frequently Reported Type/Cause of Damage
WATER SUPPLY			
Pumps and Motors			
pump-motor unit	Minor	Operative	No specific damage reported
pipe connections	Minor	Operative	Rupture due to excessive movement
supports	Moderate	Inoperative	Mountings sheared off
Hot & Cold Water Storage Tanks			
tank body	Minor	Operative	No specific damage reported
pipe connections	Minor	Operative	"
supports	Moderate	Inoperative	Mountings sheared off
Piping (air, Steam, Vacuum, Gas)			
pipes	Minor	Operative	No specific damage reported
fittings	Moderate	Inoperative	Rupture due to excessive movement
supports	Minor	Operative	Hanger assembly failure
Water Heaters			
heater body	Minor	Operative	Dents due to overturning
pipe connections	Minor	Operative	Secondary damage due to legs
supports	Moderate	Inoperative	Collapse of legs
Plumbing Fixtures	Minor	Operative	Fixture loosened from mounts
Compressors			
main unit	Minor	Operative	Generally secondary damage
pipe connections	Minor	Operative	Rupture due to relative movement
supports	Moderate	Operative	Vibration isolator failure
Fans (Air Supply, Exhaust)			
main unit	Minor	Operative	Damage due to unrestrained movement
supports	Moderate	Inoperative	Suspended and isolated supports failed

* adapted from reference 77

TABLE IV-2 (continued)

Essential Service System	Relative Degree of Damage	Consequence of Damage	Most Frequently Reported Type/Cause of Damage
Chillers			
main unit	Minor	Operative	Some damage due to shearing of support
pipe connections	Minor	Operative	Some damage due to shearing of support
supports	Moderate	Inoperative	Excessive movement when unanchored
Boilers			
main unit	Minor	Operative	Damage due to unrestrained movement
pipe connections	Minor	Operative	Severed due to differential movement
supports	Moderate	Inoperative	Excessive movement when unanchored
Duct Network			
main distribution ducts	Minor	Operative	Swaying of long duct runs;
branch distr. ducts	Minor	Operative	Breakage at bends
Chimneys, Flues & Vents	Moderate	Inoperative	Damage to boiler vent connections due to movement
HVC and Fuel Piping			
pipes	Minor	Operative	Reported failures mostly at elbows & bends due to excessive differential movement.
fitings	Moderate	Inoperative	Reported failures mostly at elbows & bends due to excessive differential movement.
supports	Minor	Operative	Hanger assembly failures
Pumps			
main unit	Minor	Operative	No specific damage reported
pipe connections	Minor	Operative	Rupture due to relative movement
supports	Moderate	Inoperative	Excessive movement of unanchored supports

TABLE IV-2 (continued)

Essential Service System	Relative Degree of Damage	Consequence of Damage	Most Frequently Reported Type/Cause of Damage
FIRE PROTECTION			
Sprinkler System			
risers	Minor	Operative	No specific damage reported
distribution mains	Minor	Operative	"
valves	Minor	Operative	"
branch pipes	Minor	Operative	"
sprinkler heads & controls	Minor	Operative	"
support hangers, bracing & clamps	Minor	Operative	"
Standpipes			
mains	Minor	Operative	No specific damage reported
risers	Minor	Operative	"
clamps & hangers	Minor	Operative	"
Pumps			
main unit	Minor	Operative	No specific damage reported
pipe connections	Minor	Operative	Secondary damage due to support movement
supports	Moderate	Partially Inoperative	Excessive movement of unanchored supports
Pressure Tanks			
tank	Minor	Operative	No specific damage reported
supports	Moderate	Inoperative	Damage due to support failure
Suction Tanks			
tank	Minor	Unknown	No specific damage reported
supports	Minor	Unknown	"
EMERGENCY POWER			
Motor-Generator Set			
motor & generator	Moderate	Inoperative	Sheared off isolation mountings
cooling components			
- radiator	Minor	Operative	No specific damage reported
- piping	Minor	Operative	"

TABLE IV-2 (continued)

Essential Service System	Relative Degree of Damage	Consequence of Damage	Most Frequently Reported Type/Cause of Damage
EMERGENCY POWER (cont'd.)			
controls	Minor	Operative	No specific damage reported
fuel piping	Minor	Operative	"
starting batteries	Minor	Operative	"
mufflers	Minor	Operative	"
supports	Moderate	Inoperative	Excessive movement of isolation mountings
Transformers			
main unit	Minor	Operative	No specific damage reported
wiring connections	Minor	Unknown	No specific damage reported
supports	Moderate	Inoperative	
Switchgear			
main unit	Moderate	Partially Inoperative	Relays and switches malfunctioned
conduits	Minor	Operative	No specific damage reported
supports	Moderate	Partially Inoperative	"
Panelboards			
housing	Minor	Operative	Overturning of tall units
conduits	Moderate	Partially Inoperative	Rigid conduit failure due to structural support failure
supports	Moderate	Inoperative	Lack of anchorage to structure
Elec. Distribution Network			
busducts	Minor	Operative	Some secondary damage due to structural failure
feeders	Minor	Operative	Some secondary damage due to structural failure
connectors	Minor	Operative	Some secondary damage due to structural failure
supports	Minor	Operative	Some secondary damage due to structural failure
Lighting			
lighting fixtures			
- recessed	Moderate	Inoperative	Separation due to ceiling racking
- surface mounted	Minor	Inoperative	"
- stem & chain suspended	Major	Inoperative	Separation of stem at structural connection; twisting of fixture

The 1972 Managua earthquake induced a landslide on the steep bank of Lake Asosoca. A pump station sypplying the majority of the City of Managua's water was supported on piling extending into the lake. The pump suctions, located one meter off the lake bottom, were buried by the landslide, requiring excavation by divers (14, 15).

Wells

Groundwater withdrawn through wells is the primary or secondary water source in many areas. Wells can be affected by earthquakes in a variety of ways. The well shaft can be crushed or sheared off by displacement of the ground across the shaft or by vibration of the ground. Ground displacements may disrupt the groundwater hydrology, decreasing or even cutting off water supply to an aquifer (16). Local soil disturbance from shaking may plug the well screen. The pump and piping may be damaged from relative movement between the units. Failure of local sewer lines or septic tanks permit sewage to leak into the aquifer, contaminating the water (17).

A well casing at the Port of Whittier was bent during the 1964 Alaska earthquake, making it difficult to remove the turbine pump. Consolidation of the strata during the earthquake caused some well casings to extend an additional six inches above the ground (18). Of seven wells used for high demand and emergency situations in Anchorage, two were lost completely; one was inoperable but repairable; two were operable but damaged; and two were undamaged. In the region of massive earthslides and liquefaction, pump lines were completely destroyed in two wells (19). Operation of two structually undamaged wells were precluded by loss of emergency power (16). In the 1952 Kern County California earthquake, many wells located in an area of surface disturbance were damaged due to the lateral displacement of the upper end of the casing.

Transmission and Distribution Systems

Water transmission systems are very important parts of any urban area's public works. History indicates that such transmission systems are vulnerable to earthquake induced damages. Seismic activity has caused either partial or total disruption of water supply pipes, aqueducts and channels in urban areas throughout the world. In some instances, the loss of vital transport systems has reulted in destruction of both lives and property.

Transport systems in this section are categorized as follows:

- o major transmission systems - tunnels, large diameter pipelines, covered conduits and open channels
- o distribution systems - buried pipelines and appurtenant structures, service laterals and connections to structures

Major transmission systems are categorized separately from distribution and collection systems in this discussion for a number of reasons. Where pipelines are used for transmission, they are often of much larger diameter than those used for distribution and are, therefore, less flexible. Transmission pipelines are sometimes laid above-ground, while distribution lines are buried.

Transmission systems are particularly crucial as they often transport a single source or one of a few sources of water to the distribution system which is commonly a network where failure of a single line will not be critical. Transmission lines must sometimes traverse long distances and unavoidably cross fault zones as is the case in the Los Angeles and San Francisco areas. Major fault crossings may sometimes be avoided with local distribution systems.

The effects of earthquakes on segments of transmission and distribution facilities can be categorized by failure mode. Damage to these facilities may be caused by seismic induced earth movements, such as surface faulting, tectonic uplift and soil failures (i.e., landslides, liquefaction and compaction of soils). The other major cause of damage is direct seismic shaking, which may induce axial and binding stresses on the structure.

Many engineers have analyzed the failure modes associated with transmission, and distribution facilities subjected to earthquakes. Damage reports from previous earthquakes and engineering analyses form the basis of the following survey of potential damage to water transmission systems.

Major Transmission Systems

This section includes a discussion of tunnels, covered conduits, open channels and large diameter pipelines. Potential damages of transmission system fault crossings, surface supported piping, seismic induced lateral earth pressures and rock tunnels are included in this section as they are more closely related to transmission than to distribution facilities. A discussion of seismic shaking, while pertinent to transmission structures, is included in the distribution and collection system subsection.

Transmission systems crossing fault zones may be subject to large differential ground surface movements. Kennedy et al. (20) points out that fault crossings are a great hazard to oil transmission pipelines traversing long distances. Relative vertical and horizontal movements of adjoining geologic blocks can exert compressive, tensile and/or shearing stresses on a transmission structure. The magnitude of these stresses and thus the extent and type of failure depends on the amount and type of relative displacement of the adjoining blocks.

Seismic shaking may induce axial and bending stresses on transmission structures as well. Transmission facilities may be more vulnerable to bending than distribution piping because of the larger pipe/channel cross sections, reducing the structure's flexibility. (See distribution piping sub-section for a detailed discussion.)

Some basic types of failures caused by the stresses identified above are outlined below:

- crushing and breaking of joints and buckling of channels and pipes due to compression
- pull-out or separation of joints due to tension
- shearing of transmission structues or off-setting of joints
- bending or shear failure of open channel and covered conduit walls due to lateral earth pressure

Other variables that determine the type and extent of damage to a transmission structure include:

- o the ductility of the construction material
- o whether the pipeline structure is above-ground or buried
- o depth of burial and backfill material used
- o the angle at which the structure crosses the fault

Some water transmission pipelines are constructed above-ground. Unlike buried pipelines which are constrained to respond as the surrounding soil media responds, above-ground pipelines' response to earthquakes depends on the forced induced on the anchor points and the structural parameters of the pipeline, which include:

- o distance between anchor points
- o the rigidity of the pipeline
- o the weight of the pipeline

A report from the oil transmission industry (20) stated that above-ground pipeline failure resulted primarily from support structure failure, attachment to the pipe and movement.

Much of the damage to major water transmission systems during the 1971 San Fernando earthquake occurred in a zone of tectonic ruptures just north of the Upper Van Normal Reservoir. Four steel pipelines with welded slip joints and one riveted steel pipeline sustained major damage. They ranged in size from 50-96 inches in diameter. Damage to the transmission pipelines were caused both by horizontal and vertical ground displacements and ground failures (landslides). The majority of the failures occurred at joints. Other types of failure included elongation or buckling of the pipe body and displacement of above-ground pipeline pier supports and ring girder anchors (13).

A 76-inch welded steel pipeline was constructed above ground on a hillside. A landslide displaced anchor piers axially, resulting in pull-out or tensile failure of mechanical couplings and welded slip joints near the summit, and buckling of the pipe body near the mid-slope. A 96-inch riveted steel pipeline was also laid above-ground. Expansion joints and the pipe body were elongated by as much as one foot. Buckling of the pipe body at pier support contacts also occurred. Damages were a direct result of the pier supports being displaced vertically and horizontally by as much as two feet due to tectonic uplift (13).

Damge to major steel trunk lines was also attributed to the combination of seismic shaking and ground movement during the San Fernando earthquake. Failures were the result of the pipe pulling apart at flexible couplings, the coupling dropping down, and the pipe, while attempting to return to its original position, crushing the coupling. The couplings involved were short couplings and used primarily for flexibility. However, they were not designed to withstand axial displacement (21).

Other major transmission facilities included concrete-lined tunnels, open channels and covered conduits. These structures were constructed from both reinforced and unreinforced concrete. The First Los Angeles Aqueduct consists of tunnel reaches lined with unreinforced concrete. The aqueduct, constructed in 1913, measures approximately 10 feet wide by 10 1/2 feet high. Although no severe damages occurred, fractures of the concrete lining, primarily circumferential, ranging from hairline cracks to 1/4 inch in width were revealed by inspection (13). Two covered box conduits, the Maclay and Chatsworth High Lines, were damaged during the San Fernando earthquake. Damage to the conduits consists of several cracks and spalling (13).

Distribution Systems

Numerous accounts of damages to water distribution pipelines have been reported from previous earthquakes. Post-earthquake surveys indicate three major causes of pieline damage:

- o large displacements (pipes crossing fault planes or pipes located in areas of surface fracturing)
- o ground failure (i.e., landslides, liquefaction, etc.)
- o seismic shaking of pipes

Pipe failure modes caused by fault displacement and surface fracturing are "straight forward". Soil failure can be predicted based on various soil paramters but prevention can be very costly. The direction and magnitude of movement after failure would, however, be difficult to predict. Therefore, there has been little emphasis put on earthquake induced pipeline failure analysis from these potential modes. On the other hand, pipeline seismic shaking allows a "straight forward" theoretical analysis. The large majority of seismic restant pipeline design analysis has been done in this area.

The following discussion will give descriptions of the types and causes of failure sustained by distiribution systems subjected to past earthquakes.

Seismic Shaking of Buried Pipelines

Response to the seismic free field, shaking or vibration of buried pipelines is one of the main causes of failure of these structures. "The seismic free field is the definition of the ground motion, without regard to its modification due to the structure to be analyzed" (21). Primary and secondary waves are chiefly responsible for direct seismic shaking of buried pipelines. Pipeline damage from earthquake shaking is primarily associated with axial pipe failure, not bending. Joint failures due to axial displacement include pull-out or separation of the joint due to tension and cracking or deflection of the joint due to compression. Pipe joint rotation can cause failure of the joint in flexure, especially on large diameter pipes whose joints will not permit as much rotation as smaller diameter pipes.

In particular, the 1923 Kanto earthquake damaged many water pipelines due to direct seismic shaking, which resulted in pipeline breaks and separation and loosening of joints. Most of the damage to the water pipeline network in Managua, Nicaragua from the 1972 earthquake consisted of pull-out of joints, loosening of bell-and-spigot joints and joint gasket displacement due to longitudinal deformation (14).

The San Fernando earthquake also caused joint failure of water and sewer pipes to occur through a number of failure modes including seismic shaking.

Joint failures included pull-out, crushing or splitting of the belled portion of bell-and-spigot joints and joint misalignment, caused by tensile, compressive and lateral forces, respectively. Joints were damaged in a wide variety of pipes, including concrete, vitrified clay, steel, riveted steel and cast iron. Table indicates the percentage of the type of water pipe with associated type of joint which had to be replaced following the earthquake (13).

Seismic Shaking and Pipeline Appurtenances

Tee junctions, valves, connections to structures, service laterals and hydrants are examples of pipeline appurtenances. Appurtenances represent discontinuities in the pipeline's structural system. Salvadori and Singhal (22) presented the results of previous tudies indicating possible stress concentrations in connections and branches 10 to 12 times those found in the pipe under non-seismic conditions.

When these discontinutities are subjected to earthquake motion, the stresses to which they are subjected may be greater than those in a straight pipe for several reasons. If a pipeline is attached to a structure, the structure may have a natural frequency independent of the pipeline's resulting in out of phase vibrations. If the no-slip assumption made in the pipeline model is correct, the pipelines, no matter what their orientation, should move with the soil with no differential response at pipe tees, elbows and thrust blocks. However, if the pipeline in fact moves with respect to the surrounding soil as suggested by a number of major lifeline researchers (23, 21, 24), pipeline discontinuties may resist this slippage, inducing local stress increases.

Fire hydrant laterals, water and sewer house connections, and other points where a pipeline forms a tee or cross intersection or branch are susceptable to seismic shaking induced damages. Damages to house connections due to seismic shaking have been reported for every earthquake included for discussion in this report. Following the 1978 Miyagiken-Oki earthquake, for example, approximately 2000 house connections were broken.

Water service connections are typically of either lead, galvanized iron, copper, or in some instances steel material. Newer construction materials for service connections include polyvinyl chloride and polyethylene.

The most common failure modes of water service connections are broken corporation valves (cocks), ball-and-socket elbows, and curb valves. Such damages result from the differential relative response of the service connection and the main (which are typically perpendicular) to seismic shaking. Pull-out of the corporation valve can result in splintering of the main where the fitting was inserted. Other types of damages include sheared couplings between the meter and curb valve and broken service pipes (25).

Valves and hydrants can also be damaged due to seismic shaking. The 1948 Fukui earthquake damaged 152 valves and hydrants (26). During the 1971 San Fernando earthquake, compression of the pipe body into gate valves on water mains broke the belled sections of valves. In instances, where compression of the main into the valve was severe, the valve was actually split in half as the two connecting pipes were pushed together (13). During the 1923 Kanto earthquake, a total of 109 valves were broken; however, the direct cause of damage was not reported (26).

Hydrants and attached piping were severely damaged during the Kanto earthquake. A total of 219 hydrants were broken, many of them located in an area where fire broke out following the earthquake. This, in addition to several broken mains, crippled the fire fighting potential of metropolitan Tokyo, consequentially, 44 percent of the downtown area was destroyed by fire.

Attached piping to structures such as storage tanks, wells, pumps, equipment, etc. often fails at the connection of the piping to the structure. Damage to pipe connections is usually a result of either differential relative displacement of the pipe and structure because of ground failure surrounding the structure, differential relative response of the pipe and structure to seismic shaking, or both. The former failure mode will be discussed in the subsection discussing ground failure and potential damage to pipelines.

In past earthquakes, many of the failures to piping attached to structures occurred as a result of ground failure. However, there are some instances such as during the 1964 Alaska (27) and San Fernando (13) earthquakes that attached piping (inlet/outlet) to water storage tanks were broken at the connection due to seismic shaking. Above-ground liquid storage tanks, when subjected to vertical and horizontal ground accelerations, can rock due to sloshing of the tank contents. Thus, strains are exerted on the rigid fitting connecting the piping to the storage tank, causing failure. Consequently, the tank contents may be drained entirely, reducing quantities of stored water for emergency utilization, and possibly resulting in a public safety problem.

Outlet piping attached to well-casings or pumps can be broken at the connection fitting due to the differential relative response of the pipe and the well to seismic shaking. Several wells experienced such damage during the Alaska (27) and San Fernando (13) earthquake. Failures primarily occur at the connection because the well casing or pump and the pipe can resist greater strains than the fitting.

Pipelines weakened by corrosion are susceptible to damage when subjected to seismic shaking. Corrosion has been known to adversely affect the seismic performance of steel and galvanized steel pipelines and is suspected to affect cast iron pipelines in a similar manner (13, 28, 29). Shaking or pressure surges due to seismic wave propagation can cause corrosion-weakened reaches of pipe to form leaks and/or larger blowouts. Some of the causes of corrosion are the contact of two dissimilar metals with water or soil, stray electric currents, impurities and strains in metals, contact between acids and metals, bacteria in water, or soil-producing compounds that react with metals.

As a result of the 1969 Santa Rosa earthquake, steel and galvanized steel mains which leaked following the earthquake did so primarily at points which were weakened by corrosion, having a leak frequency ten times the average leak frequency under normal conditions for the system. However, data were not available to determine how many areas with high leak rates under normal conditions did not experience increased leakage as a result of seismic shaking. Therefore, no conclusions for predicting leaks due to seismic shaking from normal leak rates could be drawn.

Surface fracturing (tectonic movement associated with fault displacement) and ground failure (landslides, liquefaction, etc.) are the other major causes of failure of buried distribution and collection piping.

Buried pipelines are supported by the surrounding soil strata. Surface fracturing consists of relative movement of soil masses. If these soil masses are supporting pipelines, the pipeline segments will also move relative to one another, inducing axial, bending and shear stresses on the pipe and possible failure. Pipe failure would be dependent on the pipe flexibility, surrounding soil parameters and the magnitude of relative movement.

Ground failure induced by seismic shaking may consist of liquefaction, landslides (caused by liquefaction) or soil consolidation. The soil failure may allow movement of large masses of soil taking any buried piping with it, causing pipe failure at soil mass interfaces. The soil immediately surrounding the pipe may liquify, removing the pipe support and causing a buoyant force to act on the pipe. Unsupported, the pipe may move in any direction, including floating upward.

Most of damage to the water distribution system of Niigata, Japan during the 1964 Niigata earthquake was a direct result of liquefaction, resulting in ground upheval and uneven subsidence. The soil strata in Niigata consisted of sand and silt estuary deposits often extending to significant depths (as much as 15 meters near the Shinano River) (30). The groundwater level in the area was also very high at the time of the earthquake. As a result, the earthquake caused extensive liquefaction in the area, which generated large vertical (as high as 2 meters) and horizontal ground movements.

Many of the damages to the water distribution systems of Anchorage, Alaska due to the 1964 earthquake were direct results of surface fracturing and massive ground falures. The local soil conditions consisted of outwashed sand, gravel, some glacial till and clay. Ground fractures and fissures were prominent in unconsolidated soil deposit areas. Areas of terrain in Anchorage were broken with horsts and grabens. Evidence of liquefaction was also observed through the pressure of sand boils. In the Turnagain Heights area, a massive landslide resulted in the destruction of 75 homes and the distribution and collection systems serving that area. Both joints and pipe bodies of cast iron, asbestos-cement and concrete pipelines were broken due to the shear exerted on the pipelines by surface fracturing. Connections to manholes were broken and the manholes themselves damaged by the differential movement due to liquefaction (27).

Surface fracturing also caused extensive damage to the water distribution system of Managua, Nicaragua during the 1972 earthquake (14, 31, 32). Large joints displacement and pipeline breakage was caused by surface faulting.

Pressure Surges

Water hammer (pressure surges) in water distribution systems may be caused by the sudden closing of valves triggered by seismic motions or by earthquake accelerations of the contained water responding in hydraulic reasonance. Young and Hunter (33) have shown, using a one-dimensonal analysis, that earthquake induced hydraulic pressure increases in water distribution systems may be as high as 435 psi, when subjected to a moderate earthquake. Water pressure surges in pipeline networks have been known to "blowout" water meter casings and vacuum breaker and air valve housings (13). Pressure surges have also caused blowouts in reaches of pipe weakened by corrosion.

<u>Channels, Buried Piping and Conduits</u>

Channels, buried piping, and conduits suffer from earthquakes in much the same manner as buried tankage. Differential settlement from soil densification or liquefaction of the supporting strata can cause cracking and spalling of concrete. Differential lateral movement of tanks connected by channels or piping may cause joints to separate or push together, crushing the joint. Axial waves (primary waves) generated by the earthquake may induce axial strains on channels or piping.

Lateral earth pressure on the sides of open channels or box culvert walls may cause their failure in bending or shear. Connections to tanks may crack or spall due to differential movement or vibration.

The following damages were observed in the Joseph Jensen water filtration plant as a result of the 1971 San Fernando earthquake (13):

- 1/2-inch to 3-inch openings in the joints of effluent and overflow conduits immediately adjacent to the finished water reservoir
- failure in lateral shear of a 300-foot section of effluent conduit underlain with alluvium with 20 feet of overburden, causing a lateral deflection of 3 inches

- opening and spalling of expansion joints due to one-foot settlement of influent and connecting conduits to mixing basins, in the Jensen plant; voids were found under these conduit foundations

Storage Tanks

Damage to water storage tanks is a common result of earthquakes. The loss of such facilities can seriously jeopardize the ability of a water supply system to provide sufficient water for fire protection, and to maintain a potable water supply with adequate pressure for the consumer. In addition, collapse of a tank could cause injuries and extensive property damage both from the falling structure and the rapid release of the tank contents.

The following discussions relate to storage tanks located at treatment facilities or in the distribution system. The geometry of water storage tanks often.relates to their design as either buried, surface or elevated tanks. The seismic response of each of these major types is influenced by different factors as identified in this section. Generally water storage tanks are constructed of either concrete or steel and can be either totally enclosed or open. These differences influence the response of tanks to seismic forces and the amount of damage that can be expected. Site conditions also have a major influence on the potential extent of damage, since tanks are massive structures and therefore require solid foundations.

Many water treatment processes utilize tanks for reasons other than for simply storage. Process equipment such as sedimentation basins, mixing chambers, and filters consist of structures that are in fact tanks. The response of these structures to earthquakes will be influenced to a great extent by the same factors influencing conventional water storage tanks. The only major difference being that these process items consist of some additional appurtenant structures not found in water storage tanks. Therefore the discussion of the impacts of earthquakes will include discussions of these process items with respect to the tank structure and will not address the appurtenant items (e.g., baffles, troughs, and centin wells).

Buried Tankage

Tanks are considered to be "buried" when the bottom of the tank lies below the ground surface. Buried concrete or steel tanks are found in most treatment systems. Then typically represent the largest structure in the system. In water treatment systems, aeration basins, mixing and flocculation tanks and clarifiers are typically constructed of concrete or steel. filters in both water and sewage treatment plants may also be constructed of concrete or steel. Buried finished water reservoirs (clearwells), usually of concrete, are found in many water treatment systems.

Tank walls, internal components, foundations and appurtenances are all subject to earthquake induced failure through a variety of mechanisms.

Pressures on tank walls include outward impulsive (inertial) and convective (due to sloshing) pressures from liquids, as well as lateral pressures from surrounding soils. Tank walls are commonly designed as cantilever retaining walls to resist lateral earth pressures. A standard non-seismic tank design may include provisions for resisting static lateral earth pressure, groundwater pressure and flotation. An earthquake may cause the lateral earth pressure to increase through the inertia effect on the soil behind the retaining wall. Liquefaction can also occur as the result of an earthquake, causing the internal angle of friction in the soil behind the retaining wall to be effectively reduced to zero; the resulting lateral force exerted will be that of a liquid. Liquefaction potential may be high in uniformly graded, non-cohesive soils where ground water is high.

Impulsive and convective pressures of liquid contained in the tank exert lateral forces on interior tank components such as baffles, distribution and collection troughs, aerators, piping, etc. which may also be damaged. The inertia of the mass of the actual components may in some cases exert a substantial lateral force.

Because tanks are often massive structures, the integrity of the foundation is critical. While an earthquake would have little effect on the soil pressures from the foundation, the soil bearing capacity may change significantly. Vibration of soils with a low relative density such as fill or alluvial material may cause the soil to consolidate. Liquefaction of the underlying strata may cause the soil bearing capacity to be reduced substantially. Either of these may lead to uneven settling of tank structures, causing cracking and spalling which may be so severe that gravity flow through the plant would be prevented or sharply reduced. Liquefaction of soil surrounding an empty tank may even lead to the flotation of the tank.

When tanks settle, attached piping and feed and effluent channel connections are very vulnerable. If inlet or outlet devices are broken, the tank may be rendered inoperable, even though the the tank itself is strucutally sound.

The most extensive earthquake damage to a water treatment system documented in the literature was sustained by the Joseph Jensen Water Filtration plant of the Metropolitan Water District of Southern California. The Jensen treatment plant was under construction and only 85% complete at the time of the 1971 San Fernando earthquake. A major earthslide occurred at the plant site, covering an area 2500 feet by 800 feet. The area involved moved three to five feet laterally. A pressure ridge on to two feet high and about five feet wide developed at the base of the slide. Several sand boils from liquefaction appeared in the vicinity of the pressure ridge (13). The fill area experiencing sliding had a soil relative density of about 50% (34). It is estimated that this area experienced a horizontal acceleration of about 0.4 times gravity (13). Existing structures in the northeast section of the plant moved one-half foot to one foot, causing many expansion joints to open (13).

Mixing and settling basins founded on compacted fill in the northwest section suffered uneven settlement directly proportional to the depth of fill on which they were supported; the maximum settlement experienced was five inches. This led to the opening of expansion joints accompanied by concrete spalling. Unattached launders fell off columns, and sludge collector traveling bridge wheels jumped off tracks caused by shaking.

The most significant damage at the Jensen treatment plant was the failure of the finished water reservoir concrete structure. The reservoir is 520 feet by 500 feet, with a maximum water depth of 35 feet. The roof is supported by concrete columns 20 feet on center in both directions. The reservoir roof was to have been covered with seven feet of fill to prevent potential flotation of the empty tank. At the time of the earthquake, the groundwater table was at its maximum level and only two-thirds of the fill was in place. The failure of the structure is purported to have resulted from the inertia effect of the soil overburden. Shear pressures on the roof diaphragm of 450-500 psi caused failure of the diaphragm. The roof transferred the load to the reservoir walls, causing them to fail in bending. The floor and walls underwent differential settlement of three inches to six inches, although this is not belived to be a significant cause of structural failure (13).

Extensive damage to water tanks occurred in El Centro, California, during the 1979 Imperial Valley earthquake (35). The most severely damaged facility was the water treatment plant's reactor-type flocculator-clarifier. The supporting members of the reactor unit were pulled from the tank wall anchors located along the bottomside of the peripheral wall. Several compression members within the reactor section and weir support members buckled.

Earthquake induced damages to water and wastewater treatment plant tanks also occurred in Peru (1974), Tokachi-Oki, Japan (1968), Niigata, Japan (1964) and San Francisco (1957).

Surface Mounted Tanks

For the purpose of this discussion, surface mounted tanks, generally cylindrical in shape, are those whose bottoms are supported directly by the ground with little or no burial that could provide lateral support. The majority are constructed of steel plates, either welded or riveted (old design) together. There are, however, some reinforced concrete surface mounted tanks. Tank foundations may consist of simply treated gravel or sand layers, or may be concrete ring wall supporting the tank walls.

Surface mounted tanks including their contents may be affected by earthquake motions in a number of different ways. The response of the water inside the tank is the primary driving force causing tanks to fail. The water inside the tank has been modeled based on the following response to earthquake horizontal motions (36): a portion of the water will move with the tank in short period motions; another portion of the water, primarily the top layer, will "slosh" back and forth across the tank in long period oscillations. Both of these responses will induce horizontal forces on the tank wall. In response to these forces, depending on their magnitude, the tank may slide or tip. One author noted that to his knowledge no tank larger than 40 feet in diameter with an H/D ratio less than one had ever slid due to ground shaking (20). The sloshing response may cause the tank to rock back and forth. The horizontal forces will exert a bending moment on the tank shell, exerting compressive stresses on the tank sidewall, at a maximum near the bottom of the tank. Water inside the tank is constantly exerting an outward static force on the tank wall in proportion to water depth. This loading may be amplified if the tank is subjected to vertical accelerations. With the compressive and outward forces acting on the tank wall simultaneously, it may bend outward, a phenomenon sometimes referred to as "elephant's foot" bulge. The stresses may be so extreme that the seam between plant sections may burst, allowing the discharge of water.

Another potential problem is tank foundation failure. One possible reason is the increased localized loading caused by the horizontal forces induced in the tank. The earthquake motions may cause the soil structure to break down and "liquify" or simply to compact, depending on the in-site soil conditions. This may allow the tank to tip or to settle unevenly, causing the tank shell or roof to buckle.

Reports from the San Fernando (13) and Imperial Valley (37) earthquakes indicate that tanks with rigid foundations, i.e., concrete ringwalls, are more likely to suffer from shell buckling than those with soft foundations, i.e., treated gravel or sand layers. This is probably due to increased localized stress concentrations, as the rigid concrete foundation will not deform.

Tanks are sometimes anchored to their foundations with bolts to resist rocking and sliding. Earthquakes have been known to stretch these bolts and even to rip the bolt connections out of the side of the tank. This again would allow the discharge of the tank's contents. In the 1978 Miyagiken-Oki earthquake, discharge of two oil tanks' contents was so rapid that a vacuum built up inside the tanks (lack of adequate air release) and caused the tanks to be crushed inward (38).

Tank roofs may buckle from the flexing of the tank walls. The horizontal and vertical accelerations to which the roof is subjected may cause an overload on the roof members or at the connection to the tank walls. Sloshing water may lift up portions of a tank roof, damaging either the roof or its attachment to the tank wall.

Pipes and other appurtenant items, such as stairways connected to the tank, may be broken loose due to tank movement. This movement could be caused by tank settlement, rocking or simply vibration that is out of phase with the adjacent ground to which the items may also be attached.

The height-to-diameter ratio seems to have an effect on the type and severity of damage a tank may incur. A conclusion drawn from the tank damage encountered in the San Fernando earthquake is that tanks with H/D ratios outside of the range of 0.4 and 0.7 are highly vulnerable to damage from moderate to major earthquake forces. It has also been indicated that stand pipes with H/D ratios greater than 1.5 had limited change due to reduced sloshing forces. However standpipes are not commonly used in the water supply industry.

The steel washwater tank located at the Joseph Jensen Filtration Plant measures 100 feet in diameter and 36-1/2 feet in height. At the time of the earthquake the tank was half full. The tank's foundation consisted of a concrete ring wall 14 inches thick and 3 feet deep, and the tank was located directly on undisturbed dense soils. The tank was anchored to the ring wall by 12 one-inch diameter anchor bolts, equally spaced about the perimeter of the tank. Sloshing of the tank contents set the tank into a rocking motion. The anchor bolts then either failed in tension or pulled out. The resulting impact of the tank base with the ring wall from the rocking motion caused buckling of the upper shell wall. The amount of vertical movement was indicated by the length of anchor bolt pulled from the foundation, as much as 13 inches on the south side of the tank. Other damage included stairway treads being broken away from the side of the tank (13).

Five other surface mounted storage tanks damaged by the 1971 San Fernando earthquake were located in Kagel Canyon (L.A. County Waterworks). The size of the tanks ranged from 15 to 27.5 feet in diameter and 18 to 24 feet in height. All were of welded steel construction. Horizontal and vertical movements generated by the earthquake caused slight displacement from the foundation, buckling of shells near the base and breakage of valves and fittings of attached piping of all the tanks. The tank contents of all five tanks were lost (13).

Considerable damage to surface mounted storage tanks occurred over a wide area of Alaska during the 1964 earthquake. A significant portion of the damage was caused by tsunamis and ground failure. However, this section will only discuss those damages directly attributable to ground shaking, which generated structural failure.

Table IV-3 lists a number of tanks, their characteristics and damages caused by the earthquake. These tanks stored both water and various fuels. However, the basic design of all the tanks and fluid properties of the tank contents were similar from a damage analysis viewpoint (1).

TABLE IV-3

TANK PROPERTIES AND DAMAGE CAUSED BY GROUND SHAKING FOLLOWING THE 1964 ALASKA EARTHQUAKE (39)

Tank	Diameter, (D) ft	Height (H) ft	Capacity, bbls	Condition at time of Earthquake	Damage Observed
A	30	48	--	Full of water	Collapsed
B	100	32	44,700	Full of oil	Damage to roof, top well, and roof columns
C	45	32	9,000	Full of turbine fuel	Damage to roof, top wall, and roof rafters and the bottom wall buckled
D	120	32	64,500	Full of oil	Damage to roof, top wall, and roof columns
E	120	32	64,500	Almost empty	No damage
F	120	32	64,500	Almost empty	No damage
G	110	32	54,000	Almost empty	No damage
H	90	32	36,100	2/3 full	No damage, except to the swing joint in the floating section
I	55	23	10,171	Full of fuel oil	Damage to roof rafters and top wall
J	30	40	5,000	Full	Extensive buckling of the bottom wall
K	30	40	5,000	Full	
L	30	40	5,000	Full	
M	28	40	4,368	Full	Collapsed
N	42	40	10,123	---	Buckled bottom wall
O	20	40	2,233	---	Bottom wall buckled and broke the wall-to-bottom-plate weld
P	144	56	--	---	Floating roof buckled; indications of large waves
Q	112	56	--	---	Floating roof pontoon damaged
R	49	48	--	---	Bottom wall buckled; indications of 10-12 in. uplift of the tank
S	90	48	--	Over 3/4 full	Roof-top wall connection and roof structural steel damaged
T	160	56	200,000	---	Support columns twisted and rafters damaged
U	160	56	200,000	---	No damage

Design of the tanks did not take into consideration any seismic force loadings. Their basic configuration consisted of a cylindrical steel wall, welded to a thin flat steel bottom plate which rested on the ground, and a roof plate.

Analyses of the characteristics of damage reported for the tanks identified in Table revealed the following types of failure (39):

- o Total collapse of the tank - A water tank which was full at the time of the earthquake buckled 6-24 inches from the bottom plate. Consequently, the bottom of the tank ripped loose from the tank wall on the side opposite of the buckle and the tank overturned. The cone roof was ripped off and propelled 75 yards in the direction of the collapse.

- o Roof buckling - A number of column supported, steel cone-roofs buckled. This was thought to be caused by the combination of weight of heavy snowfall, water ponding and earthquake aftershocks.

- o Failure at roof to shell connection - The roof to shell connection for most of the tanks was designed as a weak connection, to allow failure of the connection in the case of over filling.

- o Shell buckling - Circumferential shell buckling occurred on many tanks as a result of rocking of the tank during the earthquake.

Earthquakes in other areas have indicated similar damage modes relative to sloshing water, roof damage, foundation failure and breaking of connecting pipelines.

Elevated Storage Tanks

Elevated storage tanks are generally either supported by a braced frame or a pedestal. The frames or pedestals are commonly constructed of steel. However, there are some concrete elevated pedestal tanks in use.

Elevated tanks may fail because of foundation failure or rupture of the tank itself. The primary failure mode encountered is the failure of the tank support structure. The tank structure will respond to horizontal earthquake motions essentially as a single degree of freedom system, i.e., a mass oscillating on a spring. While a portion of the water inside the tank may have an independent response, its effect is normally considered to be negligible. The system has a moderately long period. The earthquake horizontal accelerations will induce stress on the various members of the supporting structure (braced frame). The structure may be simultaneously subjected to vertical earthquake accelerations, responding as a rigid system. The stresses from both the horizontal and vertical accelerations would then be combined. If the stress induced in a member is greater than its yield stress, it will yield. If the member yields enough it will fail. Once a member has failed, it will transfer the loading it was resisting to other members with possible ultimate tank failure occurring by the "domino effect."

The tower structure, having a long period response, may have a large horizontal displacement, sometimes referred to as drift. This may substantially realing the loadings on the support structure which may not have been considered in the design. The effect of eccentric vertical loading on the support structure from the weight of the supported object at an extreme horizontal displacement is sometimes referred to as the P-delta effect. These relocated loadings may cause the supporting structure to fail.

Some probable causes of tank support structure failure include:

- o Ripping of clevis or gusket steel bracing connections
- o Shearing of bolts or pins at connections
- o Spreading of clevises allowing pins to fall out
- o Failure of tie rods at threads or other locations
- o Bending of horizontal compression bracing

Other damage may include:

- o Spalling and cracking of concrete foundation
- o Stretching of anchor bolts (While anchor bolt failure has been noted, it was believed to have been a result of level action of falling columns and not directly from earthquake loadings (40)).

Support structure column buckling has historically not initiated failure. Following the 1952 Kern County earthquake where a number of elevated tanks suffered damage, direct column failure was not noted (40).

The Imperial Valley earthquake subjected eight to ten elevated tanks to ground movement. It was reported that of these, two were damaged and one collapsed. A gusset plate pulled out of a tubular column on one damaged tank with buckling of one horizontal strut. At El Centro, another tank's diagonal tie rods in the upper level of bracing stretched, horizontal compression members buckled and anchor bolts stretched. One 100,000-gallon elevated braced frame tank collapsed nearly within the bounds of its base. Failure is reported to have been initiated by cross bracing failure (37).

During the 1952 Kern County (Bakersfield, California) earthquake, 16 of 25 tanks in the area sustained some form of damage. Of 12 tanks designed to resist wind, two collapsed and seven suffered rod distortion or failure. The remaining tanks were designed to resist a horizontal earthquake acceleration ranging from 0.08 to 0.20 times gravity. Of these tanks, only one failed, with the others sustaining little or no damage. It was reported that the seismic resistant designed tank collapsed because of cotter key failure, i.e., either shearing or falling out (90).

Mechanical and Electrical Equipment

Mechanical and electrical equipment consists of similar items whether they are located at pump stations, treatment plants or auxiliary facilities. Generally these items consist of pumps, motors, control panels, compressors, small tanks, generators, chemical feeders and associated items. Until recently, little or no attention has been given to the installation of these items with respect to seismic forces, even if the building structure has been aseismically designed. Equipment is secured from lateral movement by friction only, which may be reduced substantially during an earthquake due to vertical acceleration and horizontal forces on the equipment. When equipment moves or overturns, connections such as electrical conduit and piping can easily break. Horizontal circular tanks, although stable in one direction, can easily roll in the other if they are not properly anchored. Equipment moving off its foundation can itself be damaged or can cause adjacent equipment or structures to break when they interact.

Anchored equipment, on the other hand, survived past earthquakes quite well. In the Managua earthquake of 1972, in which a horizontal acceleration of 0.39 times gravity was experienced, a diesel generator, motor control center, pumps and miscellaneous heavy equipment anchored to a base slab at an oil refinery were undamaged (41). anchored equipment in a Managua soft drink plant was damaged only as a result of debris falling from the collapsed roof (41). Major equipment with anchors designed to resist 0.1 gravity of horizontal acceleration did not suffer at the ENALUF Power Plant in Managua (1972) (15). Securing of chlorine tanks in the LADWP system prevented chlorine gas from leaking by preventing chlorine tank damage (San Fernando, 1971) (13).

Vibration isolation systems including spring and rubber mounts have a significantly higher failure rate than rigidly anchored systems. Equipment such as blowers are commonly mounted on these systems to reduce operating noise levels in adjoining areas. For the system to effectively filter out high frequency vibrations, it must be flexible; hence, the horizontal restraint must be relatively weak. If the system is not designed with snubbers to limit lateral movement, it may easily fail under seismic motion. Vibration isolation system failure is often attributable to the fact that the system is anchored to a piece of equipment only, and not to the floor.

In the 1964 Alaska earthquake, motor/generator vibration isolation mounts permitted movement of the equipment since they were not bolted to the floor (42). A survey of Managua's industry after the earthquake showed that spring or rubber vibration isolation mountings failed in all cases except where pumps were mounted on inertia blocks keyed to the foundation, with springs underneath. Keying of the blocks to the foundation behaved as a snubber, limiting horizontal movement (15).

In the 1971 San Fernando earthquake, systems without vibration isolation systems generally suffered less damage than those with isolation systems. Most damage occurred when vibration isolation systems were not bolted to both the equipment and the floor. Some isolators were torn apart. An emergency generator supported on a multi-spring vibration system collapsed. The isolators were destroyed when cast iron spring guards failed, allowing the springs to pop out even though the system was "properly" mounted. It is interesting to note that molded neoprene isolators survived with practically no damage (43).

Equipment and small tanks mounted on legs are susceptible to failure during a seismic event. Earthquake induced forces are not typically taken into account in their design. Overturning and vertical acceleration forces can significantly increase the loading on equipment legs. Rocking of unanchored equipment can amplify the earthquake induced motions. Cast iron legs have little ductility and are easily broken under the impact of rocking.

The Managua industrial survey indicated that jack-type equipment legs moved since they lack provisions for anchorage (41) and were unable to transfer shear to the equipment. In the 1964 Alaska earthquake at Fort Richardson, four cast iron legs supporting a sand filter, which were designed for static loading, failed (42). Numerous small tank leg failures occurred during the 1971 San Fernando earthquake (43).

Relative movement between flexible equipment and connecting systems can result in substantial damage. Out of phase vibration between two connected pieces of equipment can overstress the equipment and cause failure even if adequate anchoring has been provided. Banging between equipment abutting or close to a wall or another piece of equipment has been known to occur. Minor differential movement between a motor and pump, for example, can cause extensive damage if the system is operating during an earthquake event.

Flexible overhead power supplies in some facilities limited failure of electrical connections from movement of equipment during the Managua earthquake (41). A recommendation to allow adequate slack in electrical connections followed the 1923 earthquake in Kanto, Japan (44).

Failure of the equipment itself can be a major problem. There is little evidence of failure in heavy cast type equipment such as pumps and blowers, which have a low center of gravity. Taller pieces of equipment and their components have, however, been damaged during earthquakes; typical examples include taller reactor columns, cabinet-mounted equipment such as electronic instrumentation, and chemical feeders. Damages have included circuit board mounting failure and buckling of sheet metal cabinets and containers. Brittle structural components such as refractory material in incinerators and boilers and ceramic insulators have broken on many occasions. Structures supported over a relatively long span have failed as a result of differential settling of the foundation. Close tolerances must be maintained within active equipment (equipment designed to rotate or move) to prevent damage during an earthquake event.

Damage to storage tanks during past earthquakes includes failure of a fiber glass reinforced plastic tank storing potable water in Miyagiken-Oki, and the destruction of five fiber glass alum storage tanks at five different locations during the San Fernando earthquake (13). Chemical storage tanks cracked while settling four to six inches at the Jensen Water Treatment Plant (13). Differential settlement of a fuel storage tank located partially on fill and partially on piling led to its failure at the Managua Thermal Electric Power Plant (45, 15).

Breakage of stored material such as equipment replacement parts may be critical if they are required in the post-earthquake recovery period. Destruction of storage containers containing hazardous chemicals may endanger the life and safety of the facility personnel. Overturned battery storage racks, which damage or destroy the batteries used for emergency power, have significantly curtailed past earthquake recovery efforts.

The failure of electrical systems in treatment or pumping facilities can lead to severe operating problems. Secondary insulators in the main service transformers serving Managua's water supply system failed (41). Numerous internal electrical components were broken in Managua's industrial facilities (15). In the power plant at Fort Richardson in Alaska (1964), many motors were burned out, damaged by falling debris. Most burnouts probably resulted from the starting of motors under low voltage conditions (42).

Equipment systems often rely on secondary systems such as lubrication pumps, batteries for startup and cooling or sealing water. While failure of one of these secondary systems may in itself be minor, the effect on the overall system could be very serious. During the 1972 Managua earthquake, diesel generators used for standby power at the Managua Thermal Electric Plant were inoperable because of damage to several support systems: the fuel tank overturned; the cooling water lines to 3 units broke at pipe joints; compressed air for the backup starting system had not been stored, nor was there a way to generate it; and one exhaust system was crushed (45, 15). At the ENALUF Power Plant in Managua, the turbine support systems failed. Batteries used for supplying backup power to the oil lubrication pumps and valve controls fell off their racks. The turbine was damaged extensively because lubricating oil for its bearings was not delivered (15). An emergency generator at the Sendai sewage treatment plant moved six inches during the Miyagiken-Oki earthquake, breaking some electrical connections. Cooling water for the engine could not be supplied because its source, the public water supply system, had been rendered inoperable in that part of the City by the earthquake (38).

Secondary damage occurs when failure of one structure leads to damage of another. The collapse of the east outlet structure in LADWP's Lower Van Norman Reservoir allowed sand, gravel and rocks to enter the distribution system (San

Fernando, 1971). All pumps receiving water from the reservoir were damaged by sand in the pump packing and seals. Bearings were burned out when lubrication oil was flushed out by water from leaking seals. The material plugged controls, controllines, surge suppressors, flow meters, pressure recorders, pump impellers, strainers and pressure regulators.

Process Piping

Process piping is considered to be exposed piping supported on pipe hangers or blocks, as found at pumping stations and treatment facilities. Pipe failure from earthquake induced motions can result from either differential movement between two systems or vibratory motions of the pipe itself.

Differential movement may occur in many situations. Sections of buildings may move relative to one another at expansion joints or failure planes. Pipe systems may move relative to the wall through which they pass. One piping system may move in relation to another where two larg mass systems are connected by a relatively flexible link. Equipment may move differentially with respect to connected piping.

Earthquake vibrations include cyclic horizontal and vertical loads on piping systems. Failure may occur if pipe spans and pipe hangars are not designed to resist these additional loads. Piping systems react as continuous beams supported periodically. Under cyclic loading, the systems may react in various modes of vibration with the support points acting as modes. If allowed to vibrate substantially, stress building up a system discontinuities such as elbows, massive valves, attachments to equipment, wall penetrations and dissimilar points of restraint can result in failure at the weakest link, typically a joint or special fitting. Historically, many failures have occurred at inadequately designed flexible or expansion joints.

Failures in connections between pipes and equipment or among pipe sections have been observed during many earthquakes. Differential settling caused many utility connections to fail in Alaska (42), and broken building connections due to differential settlement were common in Niigata (46). In the 1971 San Fernando earthquake, many above-ground pipe failures were caused from differential displacement between equipment and piping (43). Many broken joints in concrete piping occurred in the Sendai sewage treatment plant as a result of the 1978 earthquake in Miyagiken-Oki (38). Some failures occurred in gasketed joints at the Managua Thermal Electric Power Plant, and some pipe breakage occurred at boilers, but the piping system generally performed well (45). Piping at higher building elevations in the power plant experienced greater movement and suffered greater damage (41).

Experience in Alaska (1964), Niigata (1969) and San Fernando (1971) has shown that while welded, soldered and brazed joints and mechanical couplings have survived earthquakes with relatively little damage, screwed joints have often failed at the joint threads (42, 46, 43). In Alaska, stress was developed in screwed fittings from the vibration of a long pipe section connected to a shorter leg (42).

Many earthquake induced failures in flexible joints have also been observed. In Alaska, flexible joints in cast iron pipe were pulled apart when the pipe was set in motion. Many bellows-type flexible pipe connections for thermal expansion failed due to lack of flexibility and the absence of pipe guides limiting lateral movement (42). Where flexible couplings were used between pumps and piping in a Los Angeles Department of Water and Power (LADWP) pumping station, no damage occurred (13).

The behavior of piping support systems in past earthquakes was varied. In Alaska, expansion loops in steam and hot water systems failed due to lack of bracing. As one pipe hanger failed, adjoining ones also failed due to the increased load (42). Piping and conduits suspended from the ceiling caused spalling of the plaster at anchor penetrations (18). Pipe support failure was reported at the Sendai sewage treatment plant as well. The piping support system at the Managua Thermal Electric Power Plant, on the other hand, was designed for mechanical displacements with springs and snubbers, and the system functioned well (45).

Other earthquake induced damages in the literature include:

- Lifting of pumps by tension exerted from connected piping (Niigata, 1964) (46)

- Minor leakage in the pump discharge at Tujunga Galley Pumping Station, and in the pump section at the LADWP's Roxford Pumping Station (San Fernando, 1971) (13).

- Shearing off of a valve behind the flange (Managua) (45).

It is significant to note that sprinkler systems installed in accordance with the National Fire Protection Code Standards performed well in Alaska (42).

Secondary impacts of pipeline failure can be extremely damaging. Flooding of facilities from broken water lines can severely damage electrical components. Shorted windings in motors require complete rebuilding of the motors. Instrumentation shorts can damage the complete system, requiring replacement of the electrical components as well as loss of pump control.

Structural Failure-Low Profile Buildings

Building failure from earthquakes has received much attention in the earthquake engineering field. A detailed analysis of failure modes is beyond the scope of this report. Only the basic failure modes and their relation to treatment plant facilities will be presented here.

Building foundations may fail in a manner similar to tanks, suffering differential settlement from soil densification or liquefaction, which may shear connecting pipes and conduits. The building superstructure may fail from the earthquake vibration in many ways, depending on the type of design and construction. Rigid masonry buildings, for example, react quite differently from ductile steel frame buildings.

This discussion is primarily concerned with the destruction of equipment and facilities within the failing structure. Damage from falling objects such as light fixtures, ceilings, debris from roof failure, etc., may be extensive. Differential movement of the building foundation or superstructure may damage equipment supported by it. Systems supported in more than one location, such as piping systems, are vulnerable to this type of damage.

Immediately following an earthquake, access to all facilities for damage inspection is critical. Quick exit from the building may be required to insure the safety of personnel. Delivery of and access to stored materials may also be critical. Structural failure of the building or its components may block these access routes.

Examples of building failure during past earthquakes include:

- Broken walls in the filter control building of the Rimac water treatment plant in Lima (Peru, 1974) (47).

- Crumbling of block masonry chlorination building (Tokachi-Oki, 1968) (48).

- Broken windows and hairline cracks in masonry walls of the El Centro water treatment plant (Imperial Valley, 1979). This did not interfere with plant performance (49).

- Failure of structural members in the chemical building of the Joseph Jensen water treatment plant (San Fernando, 1971).

- Settling of the control building of 4 or 5 inches relative to undisturbed rock, causing a 2-inch differential from corner to corner, in the Joseph Hensen plant (San Fernando, 1971).

Chapter V

Retrofit Techniques

Purpose and Scope

The purpose of this chapter is to present various retrofit techniques which improve the ability of existing water systems to survive a major earthquake. Experience has shown that in many areas of the country existing techniques for supporting or placing nonstructural items in water systems are often inadequate. This chapter is not intended to be utilized to prioritize retrofit techniques into categories relating to equipment importance. It only presents proven and existing procedures which alleviate deficiencies. Not all techniques should be utilized. Which items to retrofit is site specific and should be based on vulnerability analysis, feasibility analysis and economic analysis. Feasible retrofit techniques which minimize damage are:

1. Minimize the subsystem response to excitation by changing the natural frequency, increasing damping, or by providing shock isolation.

2. Anchor items whose functions will not be impaired by anchoring: otherwise constrain the motions of movable items within tolerable amplitudes and directions.

3. Reinforce support structures or redesign new support systems.

4. Ruggedize acceleration sensitive equipment.

5. Provide bypass or redundant devices, automate the switching from standard nonresistant subsystems to carefully designed emergency subsystems.

The major sources of background information for this chapter were discussions with personnel from numerous water and sewage systems, design recommendations by various government agencies and professional groups, reconnaissance reports from past earthquakes. In addition, the general technical literature was reviewed to develop concepts based on related equipment in other fields.

This chapter is subdivided into sections according to equipment and system categories. Water source facilities are discussed including intake structures and wells. Pipelines, pumps and storage facilities are discussed in the section presenting retrofit techniques for distribution systems. A detailed analysis of treatment plant facilities follows, including tankage, treatment equipment and piping. Pump stations, laboratories and emergency power supplies are also discussed in this section due to their structural similarity to treatment equipment. Surface supported and elevated tanks will be presented in the section on distribution systems.

General Considerations

Experience gained from past earthquakes reveals that increased protection against earthquakes can be provided by improving the capability of vital systems to withstand earthquake induced forces. While the state-of-the-art is still developing, there are, at present, many ways to further this goal. A comprehensive approach to the protection of water and wastewater systems should include the incorporation of flexibility and redundancy of vital components.

The principal parts of a municipal water supply system typically include:

a. Sources of water, intake structures (surface water) and wells (ground water).

b. Transmission pipelines or aqeducts carrying raw water from sources and/or finished water from the treatment plant to the municipality (may also include pumping stations and local storage).

c. The treatment facilities (may also include pumping stations and storage facilities).

d. Distribution networks taking water from transmission pipelines to the consumer.

This report will present retrofit techniques for the first three categories of water systems for the minimization of potential damage due to earthquake forces.

There are currently no widely accepted codes defining criteria to calculate seismic loadings specifically for water facilities. Although this report does not present design techniques it is recommended that modifications to existing components be analyzed for structural integrity with regards to earthquake forces. It is recommended that a copy of the Earthquake Design Criteria For Water Supply and Wastewater Systems recently compiled by EQSI (1), Inc. for the National Science Foundation, and a copy of the Tentative Provisions for the Development of Seismic Regulations for Buildings ATC 3-06 (9) recently compiled by the Applied Technology Council. Both of these references should be utilized to evaluate any modification to existing components. Although all techniques presented in the chapter are generally accepted provisions which minimize damage, every situation is site specific. Actual application of these general recommendations may not improve an existing components ability to resist earthquake damage and in some cases decrease components ability to resist damage.

Site conditions should be evaluated in order to estimate potential damage. Unstable soil conditions such as hillsides, embankments, and areas with high liquefaction potential can be altered to improve stability.

Systems and components should be analyzed under the assumption that some components or portions of system will fail during an earthquake. Redundancy should be provided where possible under the assumption that one unit may survive to provide continued service (50, 51, 52).

Supporting structures, building and foundations will not be discussed in this report since much has been presented in this area of earthquake retrofitting technology. Structural integrity of a structure that provides support to a water system component or equipment is obviously as important as that of the equipment itself. The supporting structure must be able to transfer the load induced on the equipment to the foundation. The user of this report is recommended to consult the building industry for suitable manuals such as the Applied Technology Councils Tentative Provisions for the Development of Seismic Regulations for Buildings (ATC-3) (9) for the proper analysis of supporting structure response.

The equipment structures' natural response frequency should be as high as possible, above 10 to 20 cycles per second, with a minimum of 3 cps (53). As the natural frequency decreases below 33 cycles per second, the effective seismic acceleration increases. The material frrequency can be increased by stiffening the component to make it as rigid as possible (e.g., adding cross bracing).

All equipment should be positively anchored to resist earthquake induced horizontal forces and overturning moments. Resistance to these loadings from friction alone should be altered by providing anchor bolts or similar rigid anchorage.

Connections between equipment and supply systems that independently respond to earthquake motions require flexible connections. There are few instances where rigid connections are acceptable. One example is between two pieces of rigid, rigidly mounted equipment sharing a common foundation and capable of common vibration response.

Soil Stabilization/Foundation Strengthening

When considering seismic protection requirements for intake structures, well house foundations and treatment facilities, a geotechnical study locating fault lines and traces, and areas of potential soil liquefaction, densification and other geologic hazards of the site is advised. This site evaluation can be greatly simplified if the original construction specifications and other data is available. Such an evaluation of the site can provide management personnel with a projected view of potential damage due to a possible earthquake event.

Water treatment plants and their source facilities are traditionally located adjacent to major water bodies which provide the raw water source. These locations may be situated on alluvial plains which are susceptable to liquefaction and settlement due to earthquake induced forces. Therefore, if the site is found to be vulnerable to soil densification or liquefaction construction methods are available (although costly) which can improve soil stability. These include drainage techniques which lower the groundwater table or relieve earthquake induced ground water pressure and the addition of cement or chemical grout to the soil to improve its cohesiveness. These techniques should be considered only when the potential of earthquake damage is high and could result in the shut down or complete loss of vital components of the water supply lifeline.

Drainage

For liquefaction to occur the vulnerable soil stratum must lie completely or impart below the ground water table. It is possible in some cases to lower the ground water table and thus improve the stability of the stratum in question. Drainage wells, as utilized in the solid waste disposal, industry may be installed around the existing facility to lower the ground water table. In addition, the potential pore pressure can also be altered. Following the 1971 San Fernando earthquake, vertical gravel columns were constructed at the Joseph Jensen Water Filtration Plant as a passive means to alleviate pore pressure that could develop in the soil during an earthquake.

Grouting

For significant settlement, caused by earthquake vibration to occur, the soil must be non-cohesive. The cohesiveness of the soil may be increased by grouting between soil particles through pressure grouting or intrusion grouting with cement, bitumen, or other chemicals. Soil stabilization techniques are dependent on the specific soil characteristics. The size of the soil particles, the moisture content and the chemistry of the soil are all critical parameters involved with successful grouting. A soil analysis is therefore necessary in order to properly determine the effectivenss of soil stabilization through grouting.

In some cases certain soil types are not adaptable to the usual grouting methods. Chemical grouting is most effective with partially saturated soils.

There are, however, some instances in which chemical grouting has been successfully utilized in dry, granular or fractured soils (54). Cement grouting is most widely used in gravelly sand with particle size greater than 1.5 mm. Bitemen grouting is used primarily to seal the soil stratum.

Source Facility Retrofitting

If source facilities such as intake structures are found to be highly vulnerable to seismic damage it is recommended that new facilities be designed and constructed. This new aseismically designed facility could be used as a backup or emergency intak structure. Applicable seismic design codes and principles should be utilized to guide both the design and construction phases.

Distribution Facility Retrofitting

This section presents both general and detailed design considerations of retrofitting existing water transmission system to limit damage and maintain limited service immediately following a major earthquake. The philosophy presented in this section is based on the goal which will protect a skeletonized system providing water service along the major transmission lines in systematic loops throughout the service area. Valving should be situated which shuts service off to the smaller distribution lines until these lines can be evaluated, repaired and put back into service. Retrofitting techniques to achieve this skeletonized system are presented for buried transmission lines and storage tanks.

General Consideration:

A system should be evaluated under the assumption that some components will fail during an earthquake. Redundacy should be considered as an excellent method to mitigate total loss on the system. Looping of the skeletonized system so if a single pipe fails, water can be rerouted, after valving off the break, through an alternative pipeline. Dead ends in the piping system should be eliminated by the creation of looping.

Valving is an important consideration when improving a water transmission system's ability to perform immediately following a major earthquake. Adequate spacing and strategic location of valves are key factors so that:

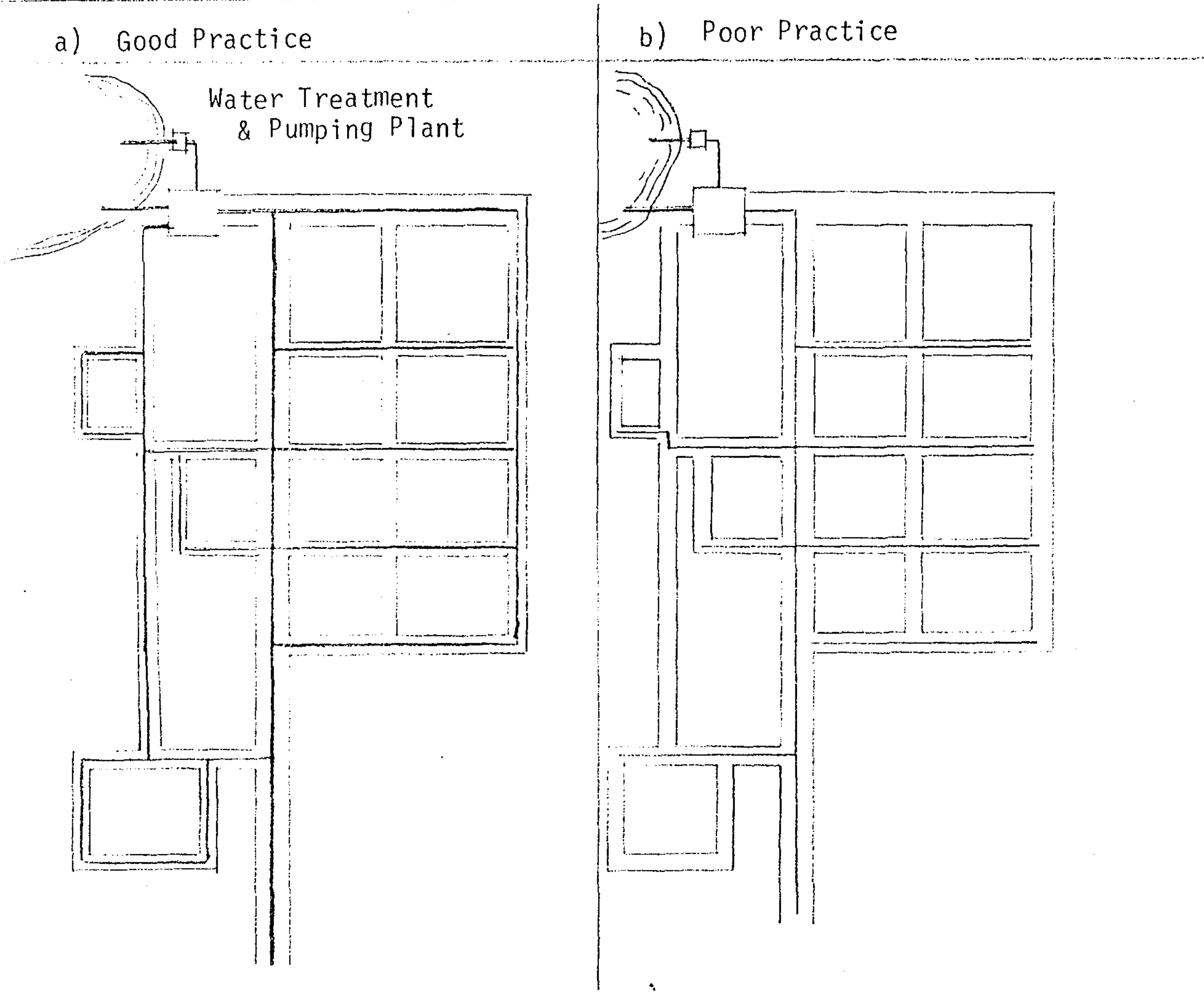
- o damaged portions of the network can be isolated for repair
- o damaged sections can be closed to reduce water loss
- o water can be rerouted around damaged portions to maintain service to undamaged communities.

In general, a valve should be located so that it can be easily and rapidly operated, repaired and maintained (50). All connections to the mains and the transmission lines deemed critical to the skeletonized water systems should have valves to protect the main from water loss due to breaks in these smaller distribution lines. In areas of high earthquake risk the installation of automatically controlled valves at these locations should be considered. The spacing of valves along individual water lines should not be more than 600 feet apart in 6 and 8 inch diameter mains, or 1000 feet apart in 12 and 16 inch diameter mains, so the length of distribution piping shut down at one time can be minimized. EBMUD requires reducing this maximum spacing of valving in areas of unstable ground (55).

Easy access to all part of the system should be provided so that in the event of earthquake damage, repairs can be accomplished quickly. System repair materials should be standardized to the greatest possible extent so that as minimum stockpile of materials is required.

It has been stated that any structure located directly astride a fault will have a very high potential for severe damage if movement occurs along the fault. When inputting redundant pipelines into the existing system, careful design and installation of a pipeline crossing a fault zone to minimize structural damage is essential. The need for redundancy in transmission lines is obvious. If two or more alternative routes are available for conveying water to a community, then damage rendering one of these routes inoperable will not cut off all water from that community.

Redundancy in a distribution network can be measured by the number of paths available from the treatment facility or storage facility to a given location. Older systems and systems in sparsely populated areas may have feeder lines with branches or dead ends as shown in Figure V-1. Increased redundancy within the system can be achieved by reducing the number of dead end lines by looping as shown in Figure V-1a (56).



Comments

Use grid system when laying out municipal size water distribution facilities. The grid system promotes maximum flexibility in water distribution.

The good practice distribution system cannot be put out of service by a break in any one line.

Figure V-1 Water Distribution Network for Municipal Size Facility (56)

Redundancy in water distribution systems can also be increased significantly if the system is connected to two or more finished water systems. The ability to isolate damaged pipelines and to reroute water with a minimum of water loss depends greatly on the strategic placement of shut-off valves throughout the distribution system. The ready isolation of pipeline breaks will minimize local erosion damage, save stored water for subsequent emergency use (57), and allow the less damaged parts of the system to be kept under pressure (32). When locating shutoff valves, particular attention should be paid to areas of likely damage, such as faults and poor soil conditions. Up to date maps showing mains, projected skeletonized systems which will serve the municipality immediately following a major earthquake, and the location of shut off valves is mandatory.

To facilitate operation under post earthquake conditions, the provision of telemetering and remote control facilities in water systems has been recommended so that information on the system's status is immediately available and changes in system operation can be readily implemented (67). Although remote control capability is especially important when road passage may be impassible during an earthquake, relying entirely on remote operation is risky because power outages and disruption of telephone lines may disrupt communications. For this reason, it is also necessary to provide for manual operation of valves (17).

Opinions differ as to the desirability of providing automatic shut off valves to prevent excessive water loss from an extensively damaged area. Having a valve automatically close due to a main break may cut off fire fighting supplies at a critical time (59). If automatic shut off valves are installed pressure-activated valves are probably more suited for seismic design than electrically-operated valves, for the latter would be rendered inoperable in the event of a power failure.

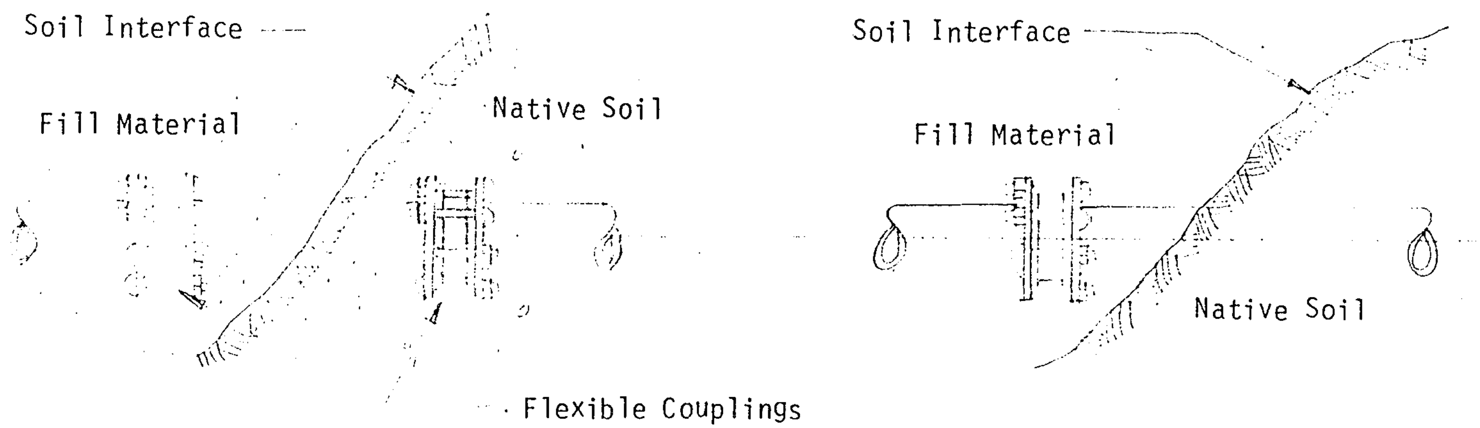
Pipe Joints and Couplings

Although this chapter will not present criteria for new design of distribution, the following section will present those components with proven survival characteristics. This discussion will assist the user of this manual in the evaluation of an existing distribution system to survive a major earthquake.

Pipe joint flexibility is an important aspect of pipe survival. Flexible pipe connections should be used in most piping systems where unusually large movements are expected. Flexibility of pipe connections to structures should also be considered. If slippage should occur between the pipe and surrounding ground, stress will build up at pipe junctions. Therefore, flexible connections should be installed where pipe movement may not be homogenous as follows:

- o bends
- o connections structures
- o valves and hydrants
- o interfaces between dissimilar soil masses (Figure V-2)

Push-on joints as well as mechanical joints provide flexibility by allowing axial, angular and rotational movement. The flexibility is provided by



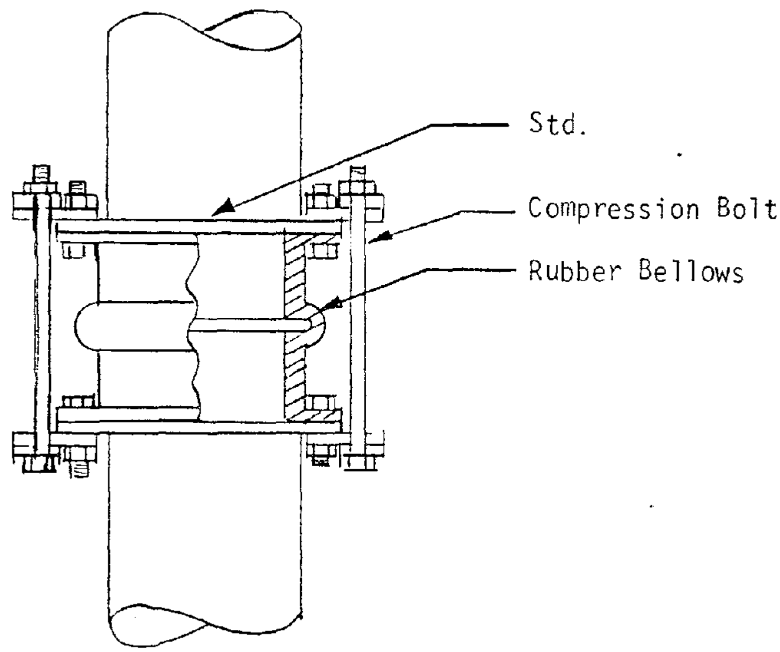
(a) Good Practice (b) Poor Practice

Comment: Better flexibility is provided by the use of two flexible couplings, one on each side of the surface separating fill and native soil.

Figure V-2 Flexible coupling installation between non-homogeneous soil strata (60, 61) the rubber gasket which maintains the seal. Rubber gasketed bell-and-spigot push-on joints allow an angular movement of 3^0 to 5^0, depending on the pipe size. They will also provide some axial movement. When the joint is installed, care should be taken to avoid pushing the joint "home" to allow for some axial expansion. Figure V-3 presents typical flexible joints.

"Pull out" of joints has historically been a problem. Where this mode of failure is expected, such as in areas of unstable soil, the push-on joints can be restrained; this would allow some axial movement but would not allow the joints to pull apart. Soil strains transferred to the pipe would then be transferred to adjacent joints. The restrained joint is similar to a push-on joint except that a separate retainer ring is attached to both the bell and spigot end of the pipe. The rings are then loosely bolted together, allowing some movement but stopping it short of pulling apart. The joint should be covered with a polyethylene or other materials to keeping the "moving pivots" free of debris. Typical restrained joints are shown in Figure V-4, V-5, and V-6.

Connections to structures, tanks and passage through walls have shown a greater chance of survival when flexible connectors are utilized. Figures V-7, V-8, and V-9 present typical pipe to structure interfacing utilizing flexible connectors.



Flexible Rubber Bellows (62)

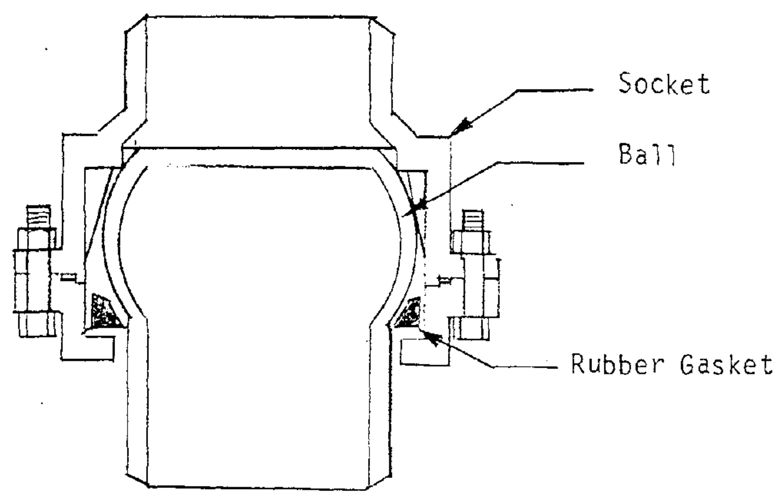


Figure V-3 Ball and Socket Joint (63).

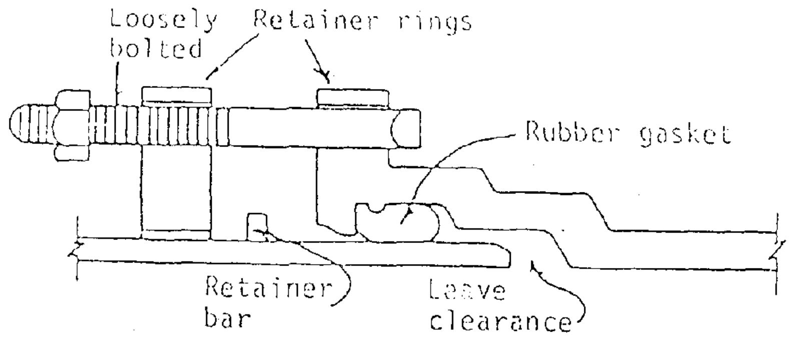


Figure V-4 Typical restrained push-on joint to permit greater axial displacement

When additional flexibility is required, restrained expansion connections can be used (see Figure V-5).

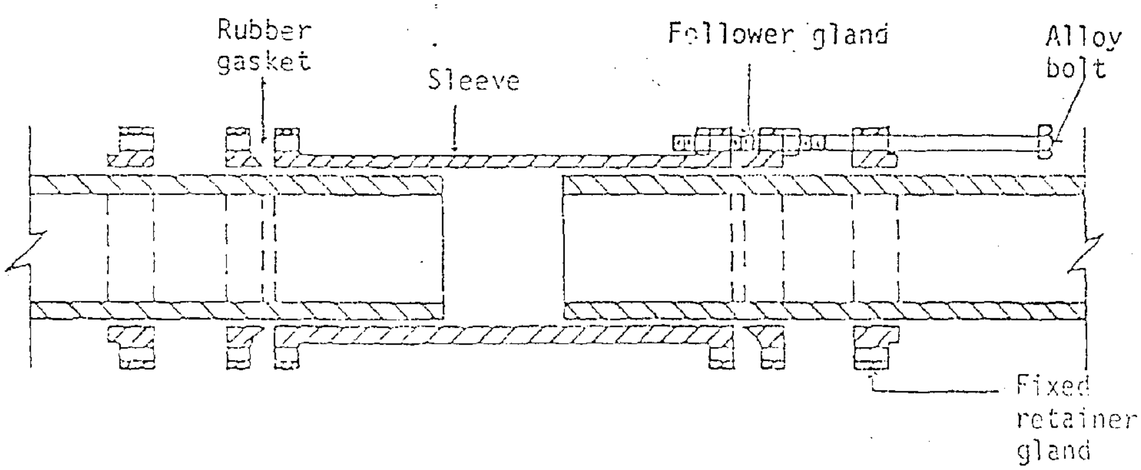
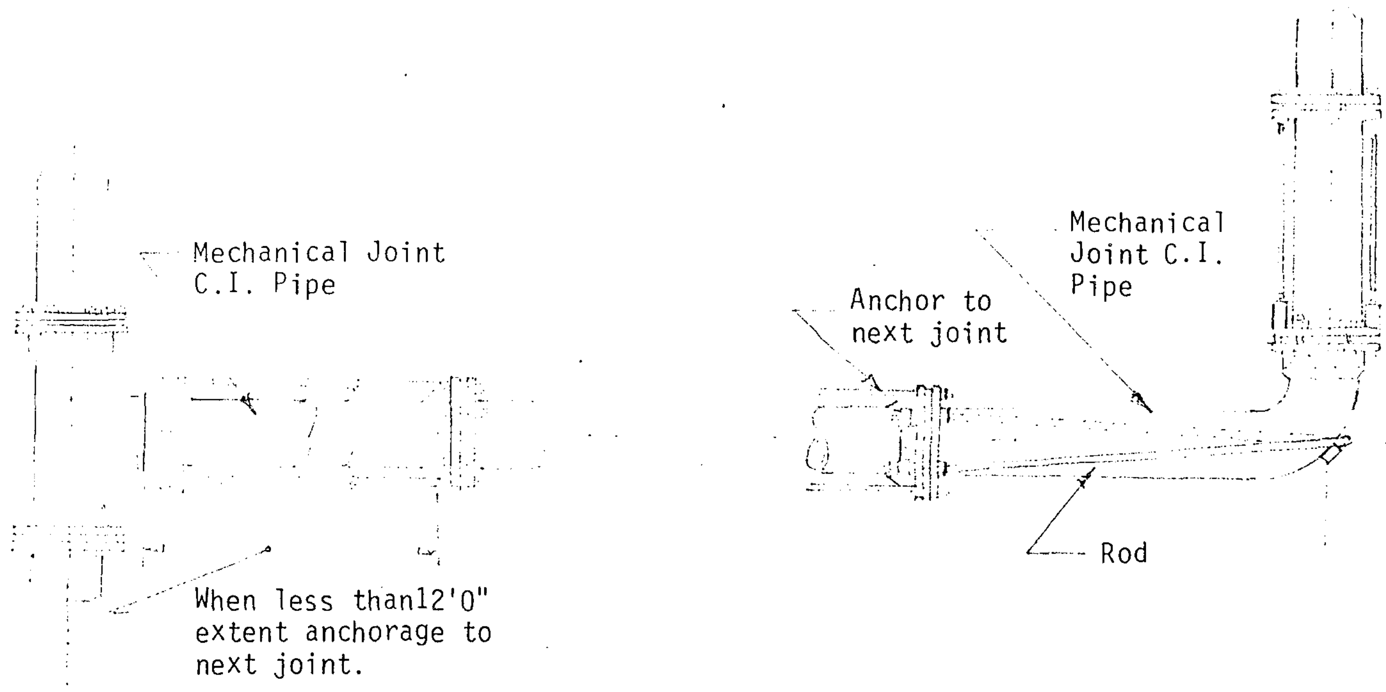


Figure V-5 Restrained expansion connection (64)



(a) Tee Joint

(b) 90^{0} Bend

Comment: Shown above are two types of acceptable flexible joints. Since anchor blocks are not required, flexible connections are not necessary for all ends of the tee.

Figure V-6 Flexible connection in installations for tees and bends (60, 61).

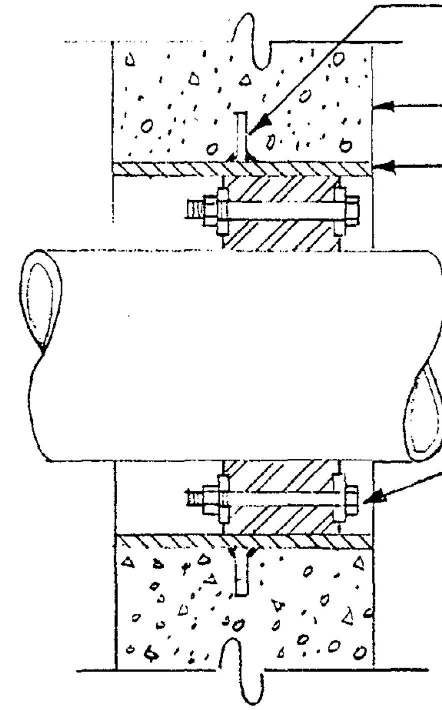
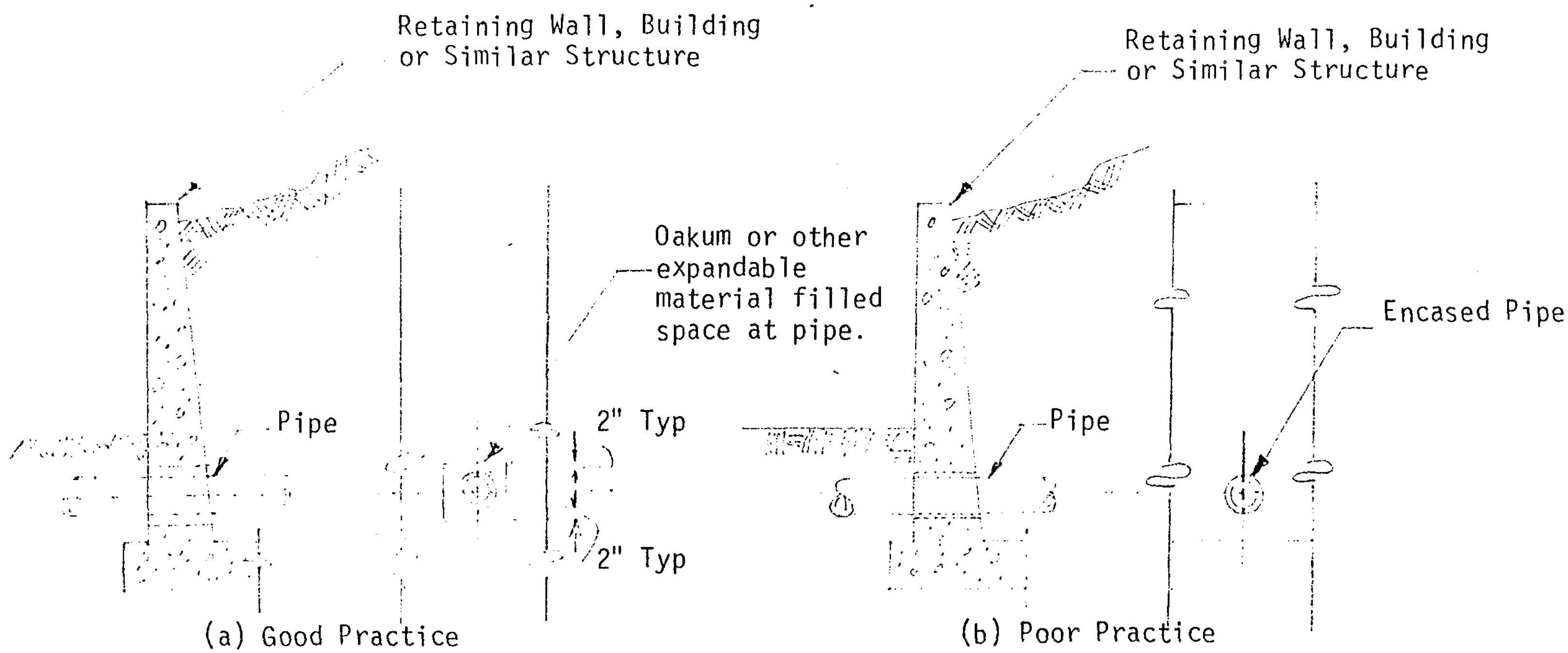


Figure V-7 Typical Pipe-Wall Penetration (63).



Comment: Allow the pipe to pass through wall without restraint.
Anticipate possible settlement of wall by providing sufficient clearance around pipe.

Figure V-8 Typical Pipe Wall Penetration (60, 61).

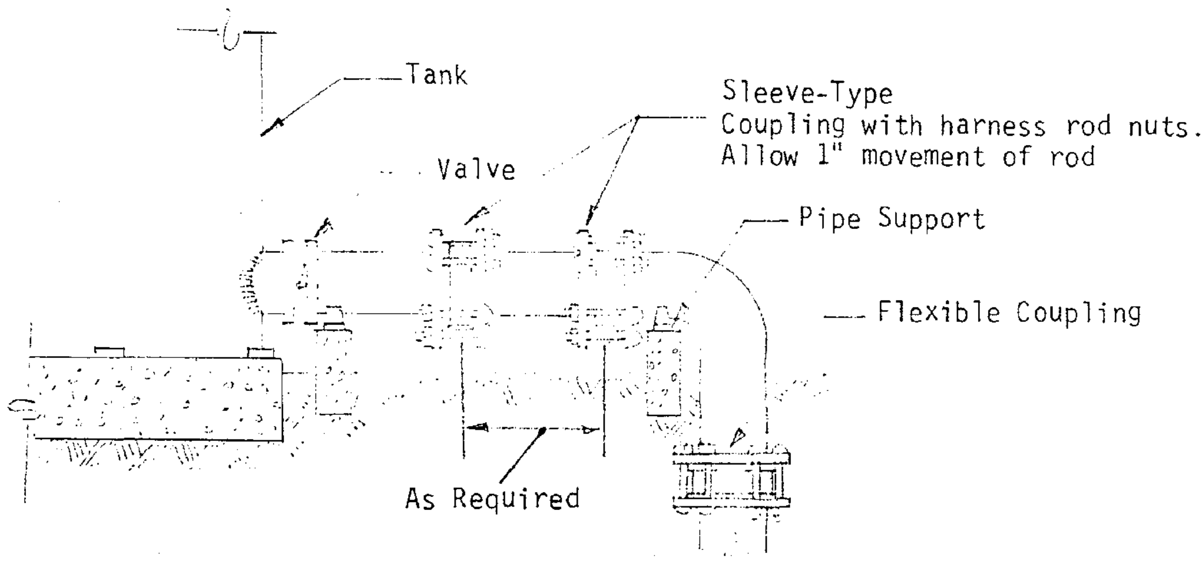


Figure V-9 Schematic of a Flexible Restrained Joint for Pipe Connection to Storage Tank (65).

Pipeline Corrosion

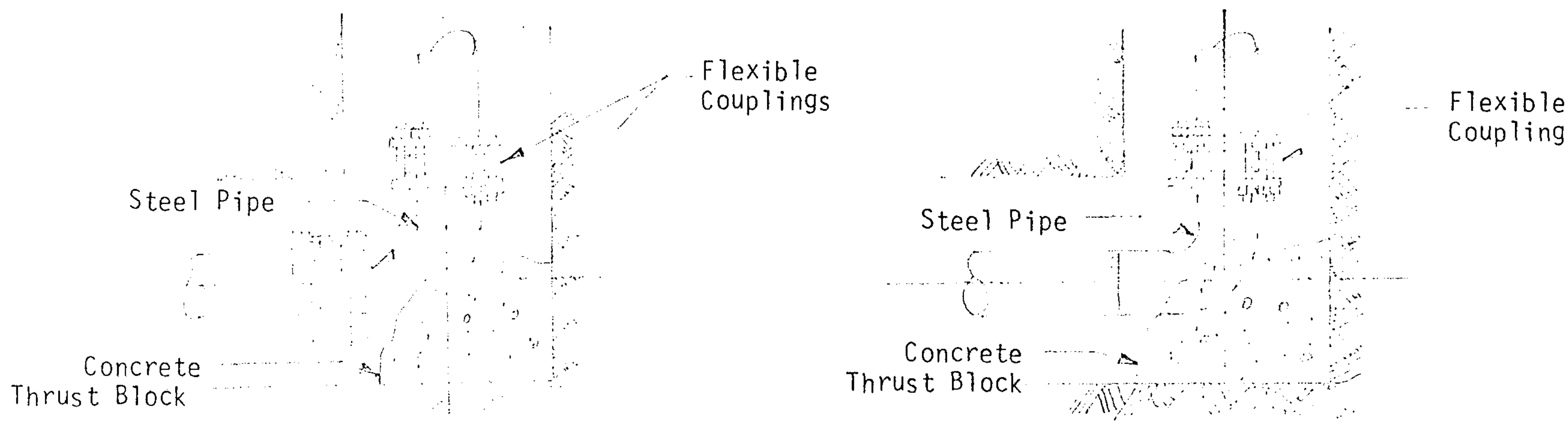
A pipeline weakened by corrosion is suspetible to damae in the form of leaks and larger blowouts when subjected to seismic shaking or ground deformations associated with ground movement and faulting. To protect buried metallic pipelines from corrosion, the following should be considered:

- o Maintain a slightly alkaline water in the system which will tend to coat the inside of the pipe with a slight calcium carbonate scale
- o Providing cathodic protection of the pipeline.

Surge Pressure

Surge pressures (water hammer) may arise from two sources when considering seismic design of pipelines. An earthquake may cause a pump to stop and a check valve, which otherwise be automatically controled, to slam shut. The dynamic response of water in the pipeline may also increase pressure considerably. When retrofitting pipelines for the installation of restrained flexible joints the use of concrete thrust blocks should be considered. Figures V-10, and V-11 present typical restraint joint couplings as installed with thrust blocks.

Valves and other fittings should be designed to withstand surge pressures, particularly where dead end piping occurs. Ductile iron has proven to be suitable to withstand significant surge pressures (64). Consideration should be given to installing pressure relief valves at critical locations.

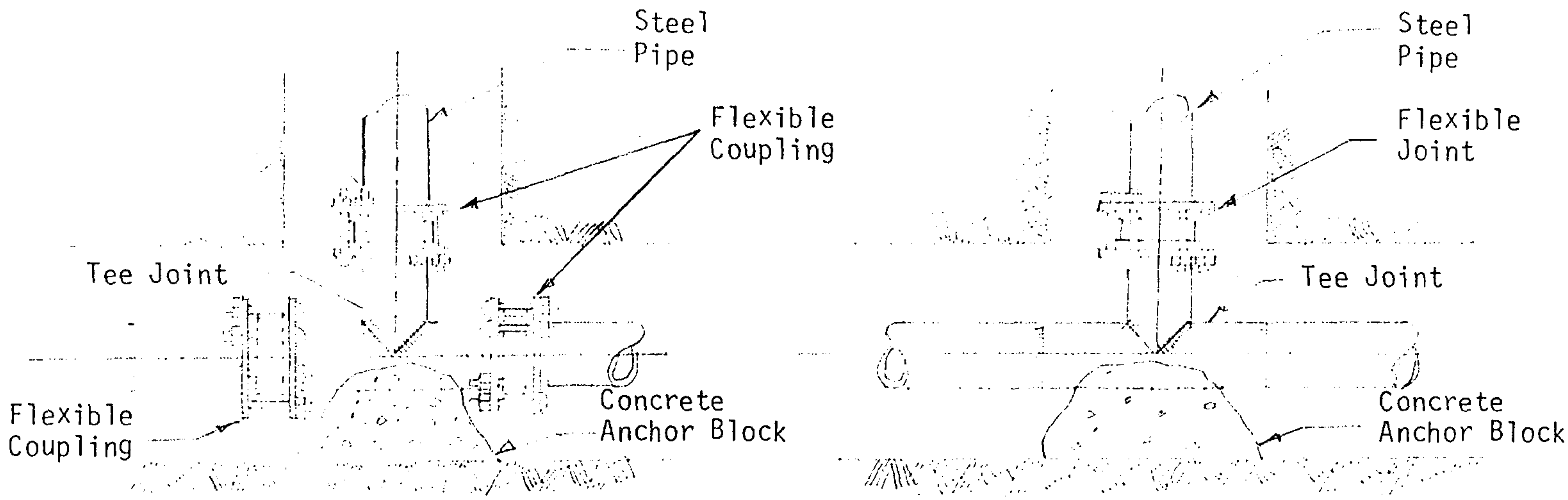


(a) Good Practice

(b) Poor Practice

Comment: For steel pipe, a flexible joint can be achieved by using flexible couplings. Proper inspection requires the thrust block not interfere with the action of the flexible coupling.

Figure V-10 Flexible coupling installation for bends with thrust block (60, 61)



(a) Good Practice

(b) Poor Practice

Comment: Good seismic design practice requires the use of three flexible couplings at an anchored tee. The concrete anchor block used to prevent the high pressure water line from separating also prevents movement.

Figure V-11 Flexible coupling installation for tees with thrust block (60, 61).

Treatment Facility and Pumping Station Retrofitting

Seismic retrofitting techniques associated for treatment plants and pump stations are similar to those utilized for the source facilities and distribution system providing operational flexibility and backup capability. This section will present typical retrofitting techniques which will improve the survival rate of treatment plants and pump stations during a major earthquake.

Recommended non-seismic water treatment plant design criteria emphasize the need for system backup, component redundancies and bypass capability as well as auxiliary power sources. Various degrees of backup capability in water treatment plants are required for rapid mix, flocculation and sedimentation units, gravity and pressure filter, pumping units, and chemical equipment (66). These backup requirements are based on potential failure on individual equipment and components; and the need to maintain non-seismic goals. In water plants, standby chlorination equipment is particularly important after an earthquake to provide a minimum treatment level of disinfected water.

Bypass capability in water treatment plant for individual units may exist. In the event of an earthquake bypass capability through the entire plant is particularly important. Maintaining hydraulic flow through a water treatment plant would insure the availability of water for firefighting or, if chlorinated, for domestic use.

Essential features of a water treatment plant bypass include adequate valving to isolate the connecting pipe section, bypass connections in a well drained pit, an inspection port normally left open with a closure plate stored in a separate location until the bypass connection is necessary, and a separate source of chlorination of the bypassed water (58).

Bypassing around a treatment plant is usually not encouraged and is often not permitted, by most regulatory agencies. The decision to incorporate a bypass, then must be arrived at jointly by the individual plant management and the appropriate public health agency. The decision to allow installation of a bypass will probably depend on developing a method for insuring that the bypass is utilized only during extreme emergency conditions.

Maintaining power is vital to the operation of water treatment facilities. Redundancy in power supply should be provided to treatment plants and pumping stations through two separate lines, each from an independent utility substation. At least one of the power sources should be a preferred source, i.e., a utility source which is one of the last to lose power from the utility grid due to loss of generating capacity (67). Although this arrangement would provide for the maintenance of power in the event of failure of one of the substations or lines.

An on-site auxiliary power system also eliminates the possible weak link of the power transmission systems. Diesel-powered generators that automatically come on-line when the normal power supply is interrupted are often used in many utilities (51). It is very important that the auxiliary power system be given a very high level of seismic protection. Often this is overlooked in the planning and retrofitting phase. Experience has shown that where backup power supplies are not protected, they will fail as readily as the main power system.

General Equipment Retrofit Techniques

The purpose of this subsection is to consider general approaches for mitigating earthquake induced damage to equipment. This subsection presents methods to reduce these induced loadings and to resist their effects. General considerations include equipment layout, support, geometry, response, rigid and vibration isolation type anchorages, interconnections and backup systems.

While the design considerations included herein are most critical for pieces of equipment required to maintain the facility's operation during and following an earthquake, their application to all equipment may mitigate damage to non-essential equipment as well. The designer should keep in mind that the failure of a structure adjacent to a critical one may disrupt the operations of the critical component; if so, both equipment elements should be considered critical.

In most cases, equipment anchorage is left up to the equipment manufacturer and contractor, withonly superficial review by the design engineer. Therefore a critical review of existing anchoring methods for seismic protection may be required.

Deflection or drift of a structure is of concern, particularly for a flexible structure where substantial deformation may occur. Such a structure may interact with adjacent equipment, causing damage. An example of this situation is a storage tank or bin extending through the floor of a room above; clearance should be allowed for in the floor penetration. Attachment of structures to both the floor and ceiling should be carefully designed, as differential displacement may also take place between the structure and the ceiling due to their respective different response characteristics.

If the mass of the equipment is large enough and located above the ground floor, it must be added to the building mass to determine the seismic response of the building. Emergency power generators and other massive pieces of equipment sometimes found on second stories are some examples.

Supporting Structures

Structural integrity of a structure that provides support to equipment is obviously as important as that of the equipment itself. The supporting structure must be designed to transfer the load induced on the equipment to the foundations. Cast iron legs, typically used as small tank supports, have historically proven to be weak and should be avoided. A wider equipment base will reduce the force necessary to overturn equipment. Manufacturers of heavy cast equipment such as pumps, mixer drive units and specialized sewage treatment equipment have claimed that their equipment bases are strong enough to resist any earthquake induced forces. These claims, however, have usually not been substantiated by actual tests or calculations.

Equipment Weight, Geometry and Response

The weight of the equipment structure (functional equipment and supporting structure) should be minimized to reduce induced earthquake loadings. Equipment structures should be as simple as possible in both plan and profile, limiting discontinuities which may allow local stress concentrations. Symetry of the equipment structure in plan and profile minimizes its torsional response. Structures with low centers of gravity have small earthquake induced overturning movement on the base.

The equipment structure's natural response frequency should be as high as possible, above 10 to 20 cycles per second, with a minimum of 3 cps (53). As the natural frequency decreases below 33 cycles per second, the effective seismic acceleration increases. The natural frequency can be increased as follows:

a. lowering the center of gravity, if possible
b. stiffening the structure to make it as rigid as possible (e.g., adding cross bracing)
c. limiting design deformation

The response acceleration to which an equipment structure is subjected is usually decreased if energy is absorbed within the structure, i.e., by increasing the damping. This can be accomplished by allowing plastic deformation of the structural materials or allowing sliding of friction joints. However, plastic deformation, yielding of the material, should be avoided for design loadings unless it will not affect the operation of the equipment or the deformed member can be quickly replaced, e.g., a mechanical fuse. Belleville washers have been used to absorb energy in mounting connections.

Rigid Equipment Anchorage

All equipment should be positively anchored to resist earthquake induced horizontal forces and overturning moments. Resistance to these loadings from fricition alone should not be allowed. Every attempt should be made to provide rigid anchorage, e.g., using anchor bolts set directly in the concrete or steel rather than providing resilient anchorage using vibration isolation systems. Vibration isolation systems have historically not performed well when subjected to earthquake motions. They are primarily used to isolate equipment operation vibrations from the supporting structure.

Anchor bolt embedments or expansion bolts should be designed to resist the loadings without yielding. However, because the design levels used in earthquake design are not the maximum that may be expected, the motions experienced may exceed those calculated. To accommodate these possible increased motions, the anchor bolt steel should be designed to yield at a loading greater than the design load absorbing energy. A ductile material should be used, i.e., not cast iron. The anchor bolt steel should be designed to yield prior to failure of the concrete embedment or critical equipment elements. Typical attachment method are presented in Figure V-12.

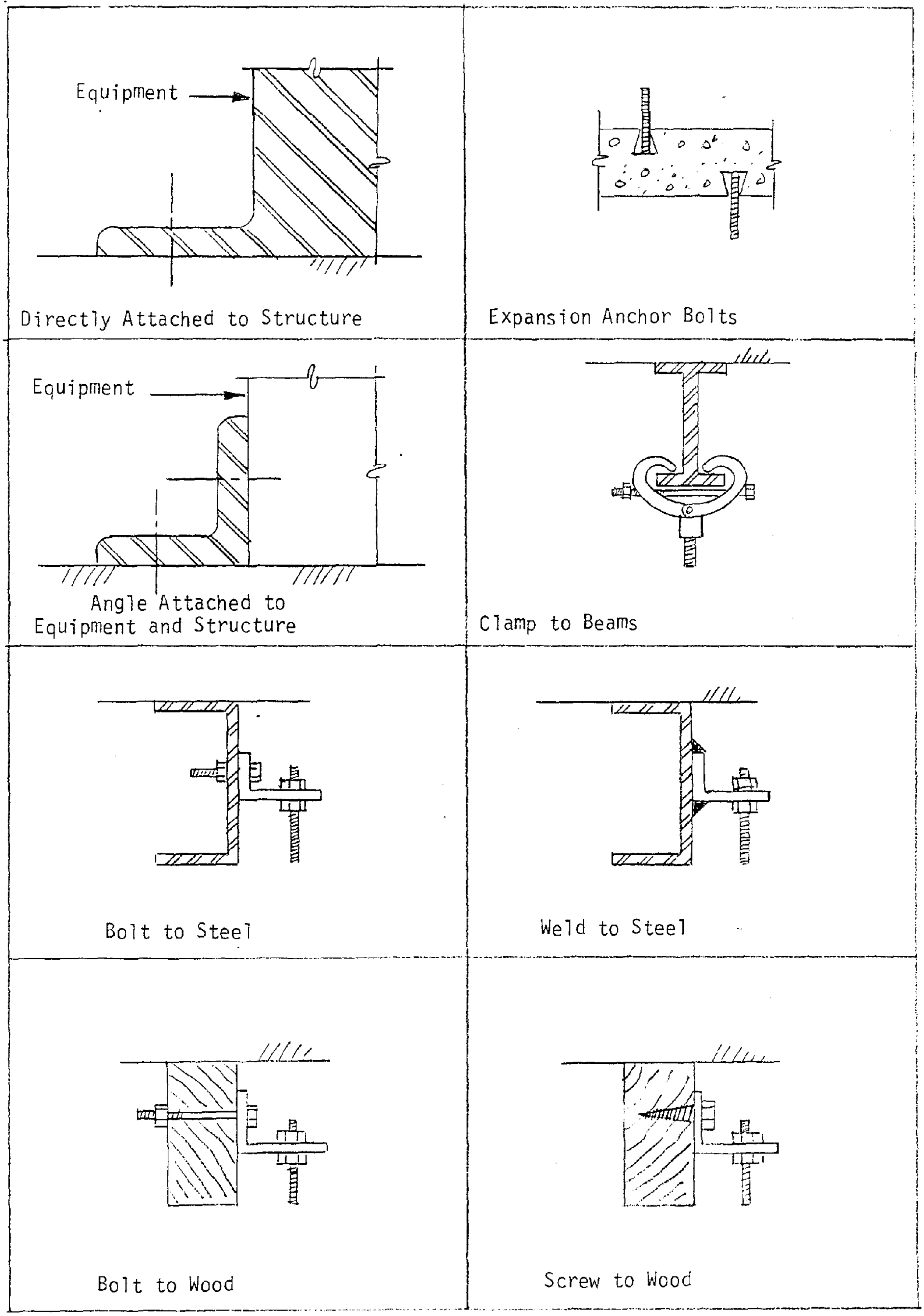


Figure V-12 Typical Attachment Methods (68).

Another approach is to use energy absorbing washers that deform in the equipment anchorage system. This will reduce the energy transferred to the equipment. Figure V-13 presents such an installation.

When expansion type anchors are used, care should be taken in drilling the holes and installing anchors. Oversized holes may result from the use of worn bits, which may not allow the specified strength of the connection to be developed. Self-drilling anchor bolt systems are recommended for this reason (69).

When shims are used to level equipment, they should provide full vertical support to the equipment base as it was designed. Failure to provide full support may allow bending of the base around the shim, allowing rocking of the structure. Stiffening of equipment bases that are not fully supported should be considered so that vibration response would not be modified by a flexible attachement (70).

Epoxy has been tested for use in equipment anchorage ("glueing" the equipment to the concrete) but has failed, as the concrete laitance layer (surface) separated from the concrete. However, epoxy has been used successfully for such items as bolt settlings.

Vibration Isolation Systems

Equipment is resiliently mounted (using vibration isolation system mounting) to filter high frequency normal operating vibrations common in

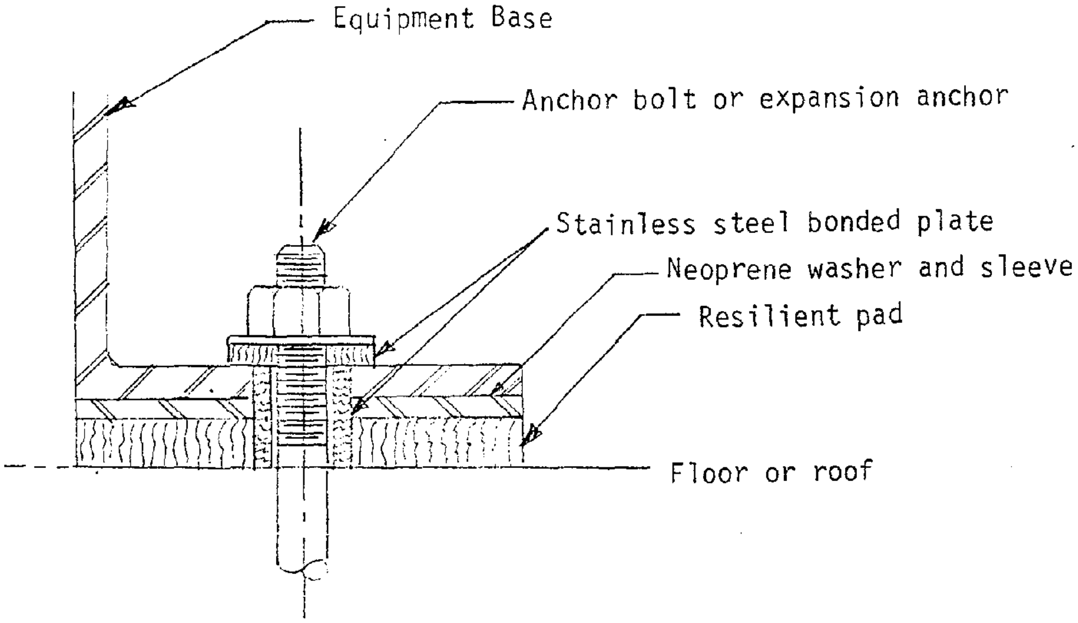


Figure V-13 Equipment restrained by resilient pads or neoprene isolators (68).

rotating equipment. Vibration isolators may consist of rubber pads, laminated rubber and metal pads, single and multi-spring systems, or rubber air bags. The high frequency vibrations are filtered in the flexible isolator, which supports the structure. The resulting system has a lower natural frequency and is therefore usually subjecting the system to amplified earthquake accelerations. Because of the flexibility of the system, it usually has limited strength for resisting earthquake induced motions. The vibration isolation system may become the weak link in the equipment's support and anchorage system.

The best way to mitigate damage to vibration isolation systems is to make them respond as rigidly anchored systems when subjected to earthquake motions. This can be done by installing snubbers or restraints to limit the displacement to that normally encountered during the operating modes. A positive seismic activated locking device that will lock out the isolation system during an earthquake may also be used.

Figures V-14, V-15, V-16, and V-17 show typical vibration isolation system mounts.

Equipment should be mounted and operated before restraints or snubbers are installed to assure that there is adequate clearance for normal operating vibrations.

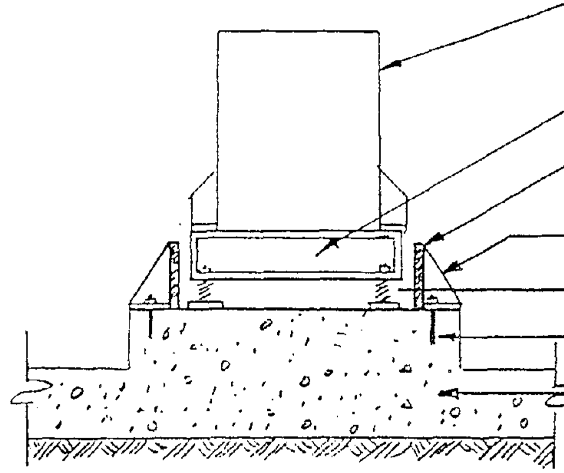


Figure V-14 Typical Installation of Vibration Isolation with Inertia Stops (71)

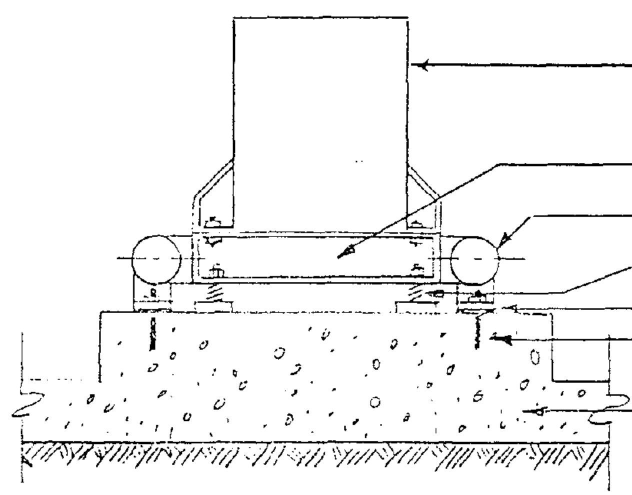


Figure V-15 Typical Installation Isolaction with Snubbing Device (Mason Industries) (71)

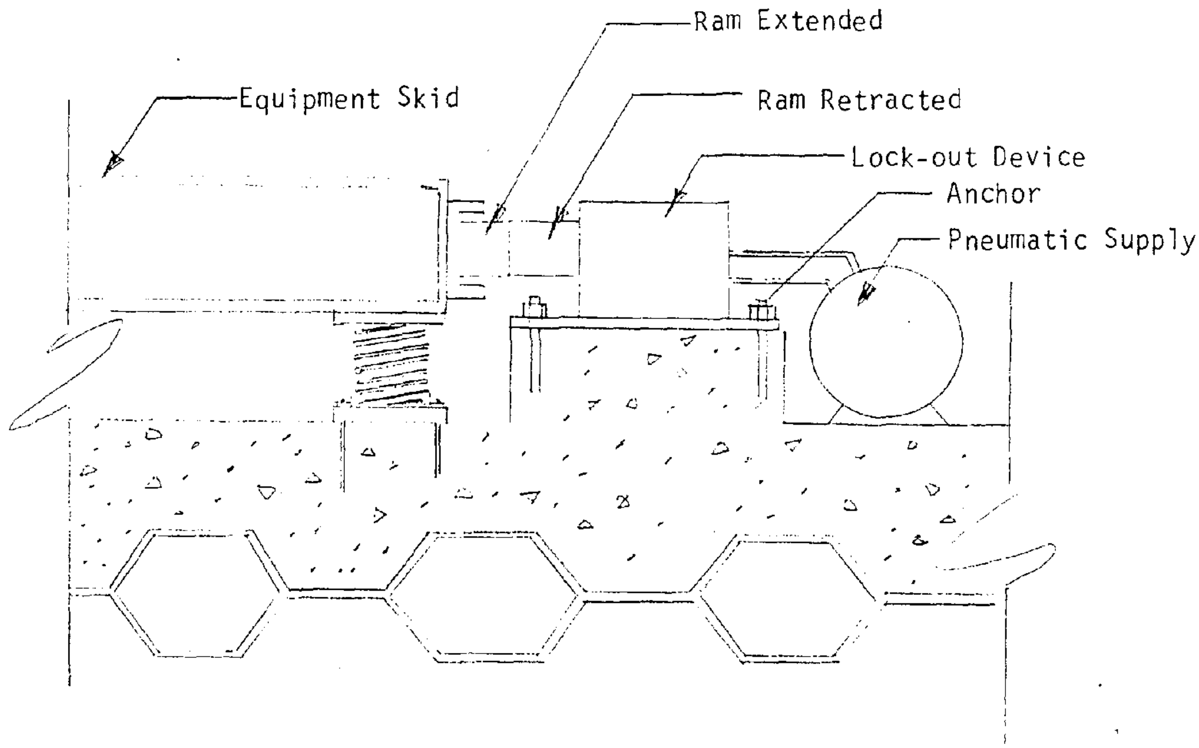


Figure V-16 Detail of Lock-Out Device (71)

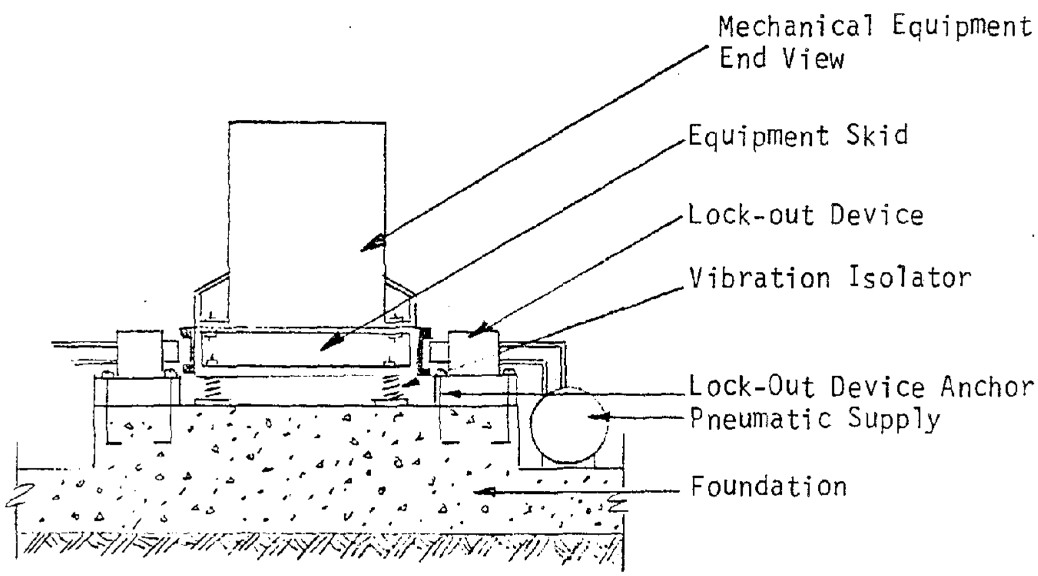


Figure V-17 Typical Vibration Isolation
Lock-Out Device Installation (71)

Equipment Connections

Connections between equipment and supply systems that independently respond to earthquake motions require flexible connections. The following are examples of such types of equipment installations:

a. Between equipment on different foundations

b. Between equipment on the same foundation but with significant independent vibrations.

c. Between equipment and piping unless the pipe is short and rigidly supported.

d. Between equipment mounted on a vibration isolation system and all connecting systems.

e. Between equipment and feed lines mounted on structures not responding with the floor (interior partitions, or non rigid type construction) See Figure V-18.

f. Between systems mounted on both sides of a building construction joint. See Figure V-19.

There are very few instances where rigid interconnections should be used. One example is between two pieces of rigid, rigidly mounted equipment sharing a common foundation and capable of common vibration response.

Flexible connections for piping will be discussed in the following section. Other types of connections allowing flexibility include flexible conduit, flexible tubing, flexible canvas or rubber sections of duct work, slip joints, and mounting clearances.

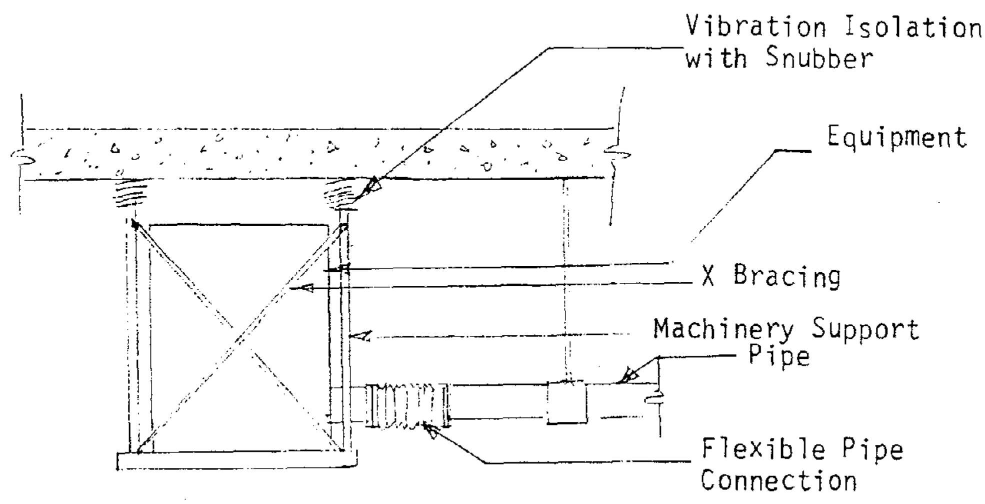


Figure V-18 Flexible Pipe Connection at Machinery Interface (71)

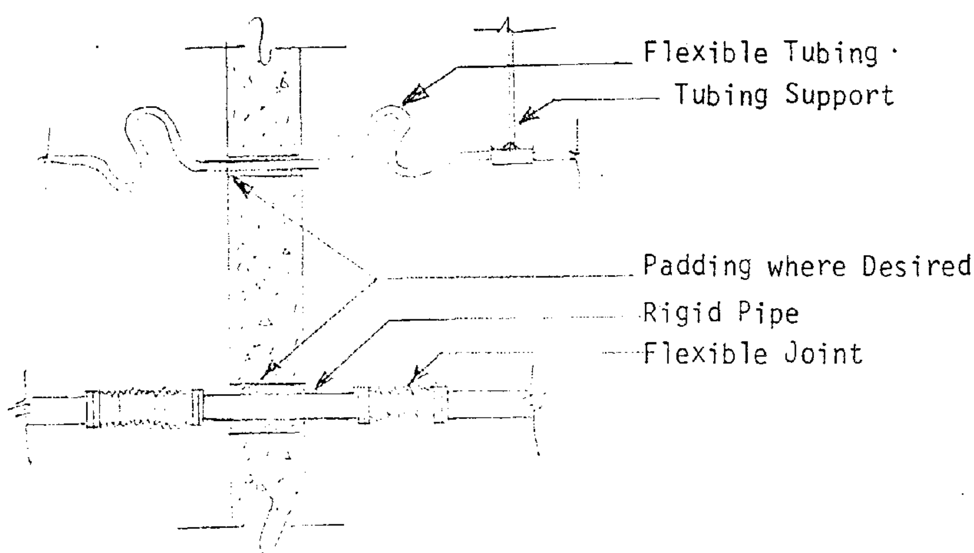


Figure V-19 Piping and Tubing Installation Through Partition (71)

Some examples of the types of interconnections recommended for specific installations are as follows:

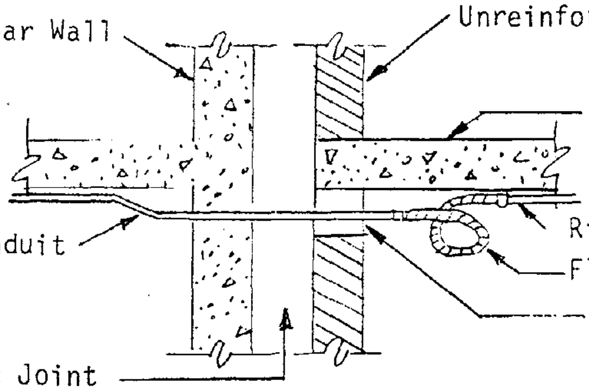
a. Horizontal pump motors connected by a drive shaft should be mounted on a common foundation.

b. Where vertical pumps are driven by a drive shaft powered by a motor on a motor floor some distance above, the entire installation including the supporting structures should be rigid and respond as a single unit.

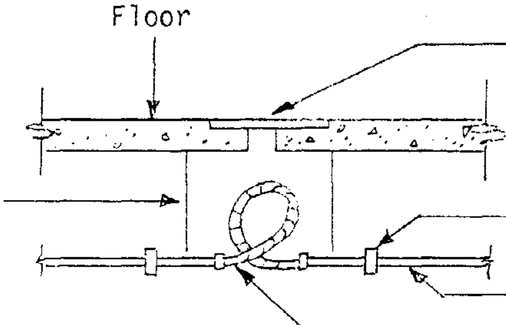
c. From a seismic response standpoint, close coupled pump-drive units are better than those supported by separate structures which may allow relative displacement when responding to seismic motion.

d. Small diameter feed lines such as fuel lines for emergency power generators, electrical conduits, and instrumentation lines should be flexible enough to respond with the structures to which they are attached and to accommodate differential movement between adjoining structures to which they are attached. Small diameter lines crossing flexible building joints and flexible equipment mounting interfaces should allow for that flexibility in their design, as shown in Figure V-20a and V-20b.

e. Critical, small diameter lines such as emergency generator fuel supply lines should be encased in a conduit to protect them from falling debris during an earthquake.



(a) Suggested Corrective Measure for Conduit Crossing a Seismic Joint



(b) Suggest Conduit Seismic Joint Crossing

Figure V-20 Typical Seismic Joint Crossings (42)

Design Considerations for Specific Equipment Types

This subsection is presented on the basis of equipment structural characteristics. The equipment listed in each category are presented as examples of types commonly found in the water treatment industry. Specific categories include: heavy cast equipment, small tanks, sheet metal structures, cranes, precision equipment, emergency power systems, immersed equipment, lab and office equipment, hydraulic equipment liquified gas storage and handling systems, primary mechanical systems, secondary mechanical systems primary electrical systems, secondary electrical systems and chemical storage systems. These examples will aid the public utility management personnel to understand and evaluate potential damage modes of said existing equipment due to seismic forces. The retrofit designs should follow the principles outlined in ATC-06 (9) as presented in Appendix A.

Cast/Heavy Frame Equipment

Examples:

a. Pumps - vertical, horizontal, submersible, detached, close connected

b. Blowers - centrifugal, positive displacement

c. Flocculator/Mixer/Aerator (platform mounted) drive units

d. Motors

Considerations:

a. To resist shear and overturning, rigid anchorage is suggested as presented in Figure V-12.

b. Flexible pipe fittings are recommended when such units are connected to pipe systems.

c. Deflection of rotating components should be analyzed in respect to earthquake forces.

d. Low voltage and single phase protection should be provided.

e. Where vibration isolation exist, snubber systems should be installed.

Primary Mechanical Systems

Examples:

Motor and Pump Units (horizontal)

Motor and pump units (vertical)

Mechanical Sludge Withdrawl Systems

Sludge Pumping Systems

Considerations:

a. Motor-pump units should be anchored to the same base pad or foundation to avoid mis-alignment problems resulting from a seismic event. In situations where the motor and pump units are not anchored to the same foundation, structural steel bracing should be installed (via bolting) between such units to avoid mis-alignment. In addition a flexible type coupling should be installed in order to provide for continuous operation if minor misalignment does occur.

b. Motor-pump units, when bolted to the same base pad, of frame are stable against overturning in most situations in all earthquake zones. In order to resist the lateral forces associated with a seismic event, where a pump system is to be supported directly to its support structure, anchor bolts to transfer lateral forces should be installed. The pump unit is supported by a vibration isolation system, snubbers should be installed which will hinder lateral movement. Typical snubber installation are presented in Figures V-14, V-15, V-16, and V-17.

c. Vertical pump units with motors located on the upper floor levels and pump units located on lower levels require adequate flexible couplings or universal joints at the pump shaft. Such an arrangement will allow continued operation if differential movement should occur between the pump unit and the motor unit.

d. Sludge removal devices such as motor driven rotating scrapers in circular or rectangular sedimentation basins should have torque arrestors installed which will detect any resistance encountered by the sludge scrapers and shut down the driving motor thus preventing further damage the driving unit. The system should not be restored to normal operating condition until the source of resistance is located and relieved.

e. Traveling bridge type sludge collectors with tracked wheel systems should be retrofitted with a wheel restraint system which will restrict the wheels from jumping the tracks during a seismic event.

Secondary Mechanical Systems

Examples:

Ventilation Ducts

Heating and Cooling systems

Hot Water Tanks

Considerations:

a. Ventilation and heating duct systems are typically hung from the ceiling. To provide lateral stability and protect against the unit falling due to a seismic event additional lateral anchorage connections are required. Various tyes of support systems and seismic lateral restraint mechanisms are present for ceiling hung duct systems.

b. Unit heaters hung from ceilings are typical to most treatment plants. Typical heater units are supported by an angle frame system at each end. Installations may require additional lateral bracing.

c. Fan units hung from ceilings are typical units found in mechanical rooms treat similar to unit heaters (72).

Miscellaneous Tanks and Small Tank Like Structures

Examples:

a. Mixing tanks - steel, fiberglass, chemical, polymer etc.

b. Carbon adsorption columns

c. Chemical storage tanks

d. Hot water tanks

Considerations:

a. Rigid anchorage should be added to resist shear and overturning i.e., anchor bolts or bracing.

b. A structural analysis should be performed assuming that the tanks maximum contents will respond with the tank.

c. Buckling stress developed in the tank should be analyzed with respect to a combination of overturning and vertical accelerations.

d. Attached piping should have flexible type connections near the joint.

e. Brittle support legs, e.g., cast iron, should be replaced with steel support systems and anchored to the support structure.

Precision Equipment, Electronic Instrumentation and Controls

Examples:

a. Chlorinators and instrumentation including analyzers, recorders, etc.

b. Meter electronic instrumentation

c. Electronic switching gear

d. Equipment instrumentation

e. Computer systems

f. Communication systems

Considerations:

a. This type of equipment should be mounted as rigidly as possible to avoid amplification of seismic accelerations.

b. Positive locking devices should be used to hold circuit boards in place.

c. All mechanical switching components, such as relays, etc., should be analyzed in respect to their seismic response characteristics. Mercury switches should be replaced. In addition gravity and light spring controlled switches should be avoided. It should be noted that relays have responded adequately in the energized position but have failed in the non-energized position.

d. Communication equipment should be provided with an emergency power supply, possibly batteries as well as the plants standby power supply.

e. All automatic control systems should have manual overrides.

f. Critical installations, such as computer systems, that cannot withstand seismic motion may have to be repositioned on a floor vibration absorbing system designed to alternate seismic motion.

Frame/Sheet Metal Structures (not including contents)

Examples:

a. Dry chemical feeders, hoppers and storage bins

b. Cabintry of chlorinator and liquid chemical feed systems, residual analyzers, etc.

c. Instrumentation cabinetry

d. Lab cabinets

e. Equipment and control consoles.

Considerations

a. Install rigid anchorage to wall, floor and/or ceiling as applicable. (See Figure V-21)

b. These structures may be supporting large masses, such as chemicals or electrical components, which may induce large forces under earthquake conditions.

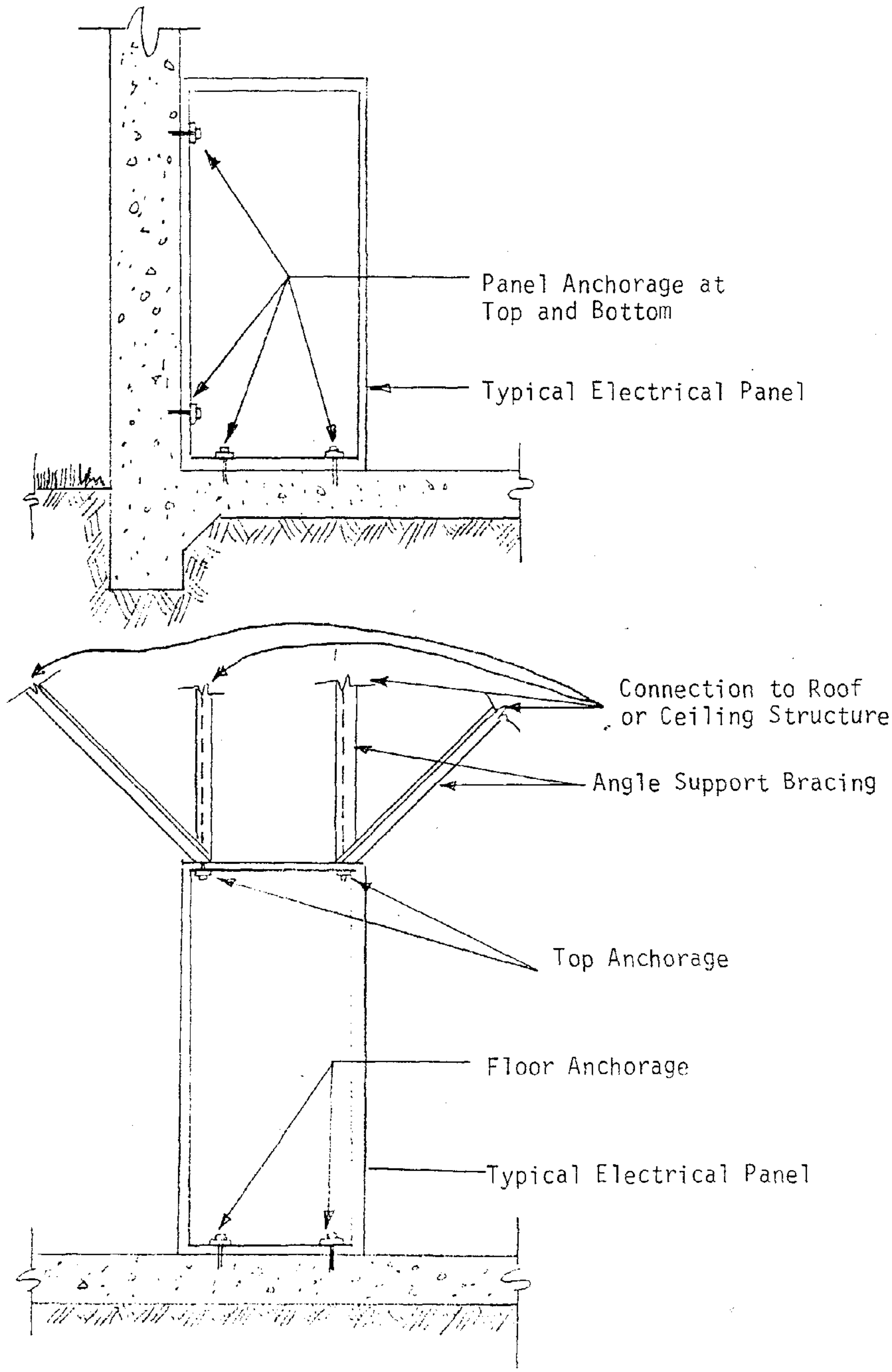


Figure V-21 Typical Electric Panel Restraints (71)

c. Sheet metal panels may act as diaphrams, transferring induced shear to the support pad. Steel and sheet metal joints must be strong enough to transfer loading. Additional bolts or welds may be required.

d. The rigidity of the structure should be maximized or improved using cross bracing, etc.

e. Storage cabinets should have stored material placed as low as possible. The use of upper shelves to store heavy materials be avoided.

f. Structures with doors or removable access panels should be analyzed for seismic rigidity. Door joints will generally be incapable of transferring a load. Multi-latch closures may be added to provide structural continuity across the joint.

g. Positive cabinet and file latches rather than magnetic of friction closures are recommended to resist seismic motion.

h. Laboratory cabinets should be lined with rubber mats to resist glassware breakage.

Liquified Gas Storage and Handling

Examples:

a. Chlorine cylinder scales

b. Chlorine cylinder storage

c. Tank car storage

d. Chlorine cylinder connections

e. Welding gas storage and handling

f. Overhead cranes and trolleys

Considerations:

a. All references to chlorine shall include other hazardous chemicals

b. Chlorine scales should be equipped with snubbers to prevent lateral motion with positive tank anchorage to the scales.

c. All gas cylinders should be chained or blocked to prevent overturning or rolling (see Figures V-22 and V-23).

d. Railroad tank cars should be blocked to prevent rolling. In addition tank cars should be restrained to avoid "jumping" the track.

e. Chlorine lines should be protected from falling debris by the use of protective type conduit.

f. Pressurized chlorine feed lines may cause severe difficulties when ruptured. Vacuum type feed lines are considered safer, since leakage is minimized when ruptured. A seismically induced shut off valve should be installed directly on the cylinder itself. Such a system would shut down when seismic induced motion is detected. This system should not put back on line following the seismic event until a proper damage assessment is completed.

g. Chlorine solution feed lines should be kept short as possible. In addition a flexible lead based or plastic type line is recommended over rigid type feed lines.

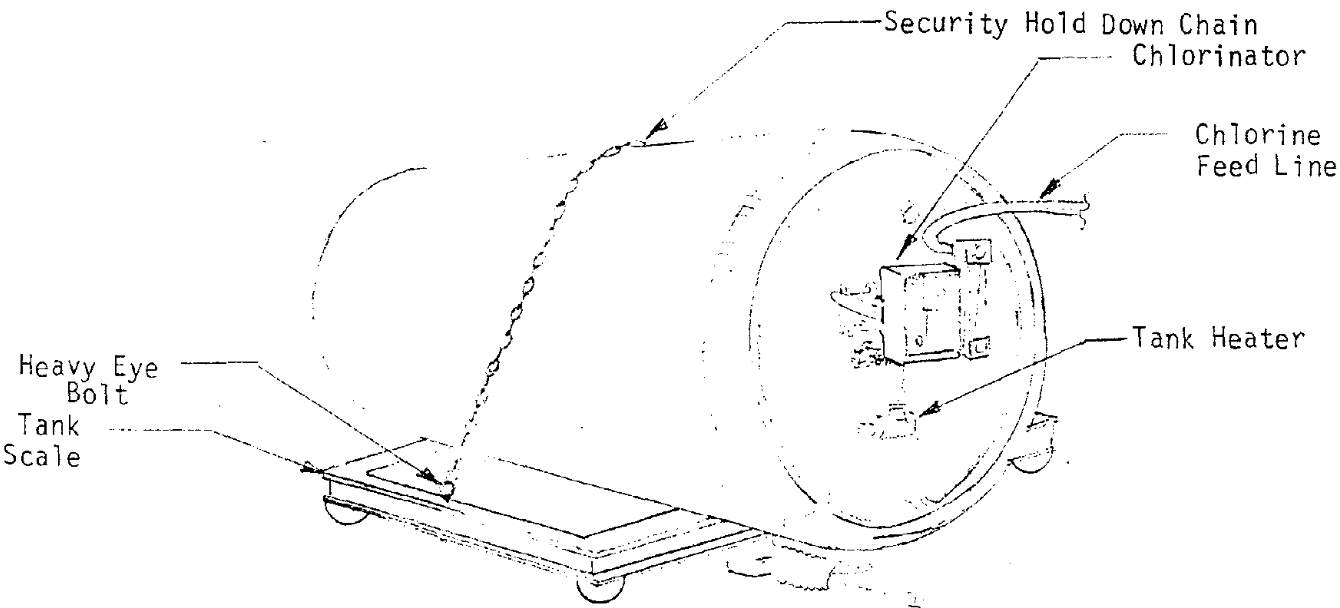
Primary Electrical Energy Systems

Examples:

a. Transformers

b. Substations and Switchgears

c. Control Panels



Comment: Snubbers or vibration isolation restraints are recommended for chlorine tank scales, since scales behave similarily to vibration isolated equipment under seismic loads.

Figure V-22 Suggest Chlorine Tank Restraints (71)

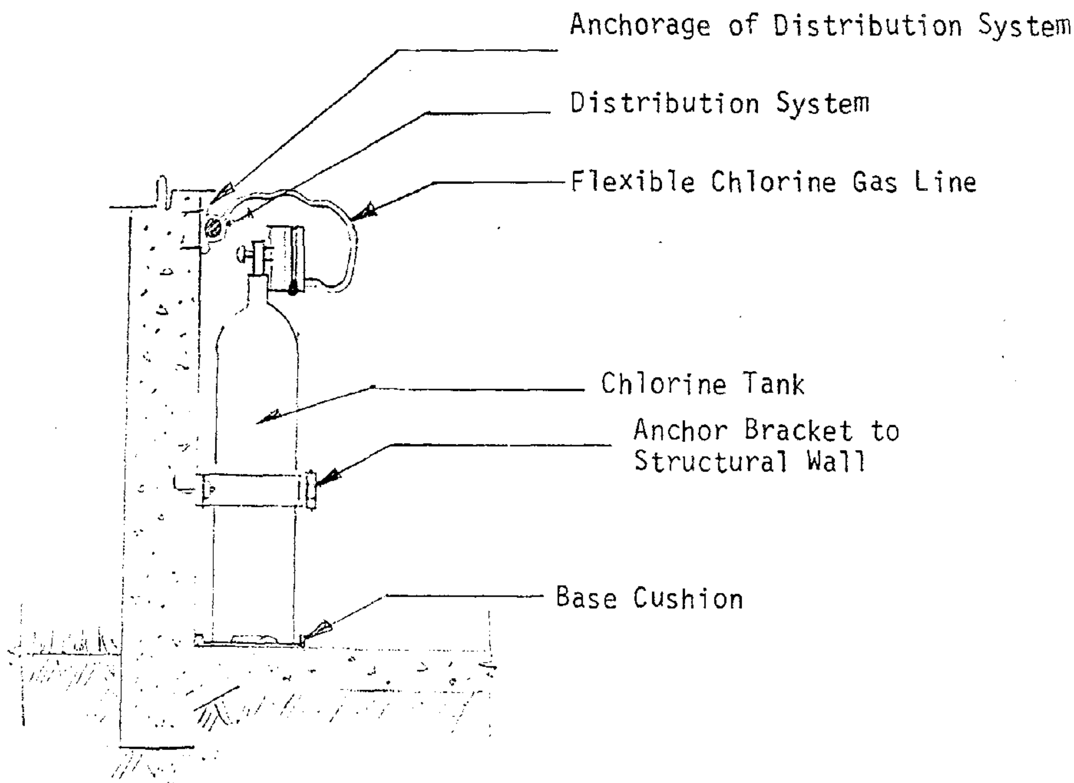


Figure V-23 Typical Chlorine Cylinder Restraint System (71)

Considerations:

a. All transformers should be rigidly mounted to their supporting structure. All transformers on grade should be anchored to the supporting concreted slab via anchor bolts.

b. Roof mounted transformers should be avoided. If replacement is not feasible the raised transformer should be adequately anchored.

c. Pole mounted transformers are attached to the utility pole by the two following common methods:

   1. Two support lugs, which are part of the transformer, fit over two thru-bolts in the power pole. These bolts are tightened after the transformer is positioned. The "jump proof" lit on the top lug prevents disengagement between pole and transformers.

   2. A bracket, that has a "Y" shaped arm, hooks over the cross-arm of the power pole. The transformer is attached to this bracket with a lug clip. a chain is passed through the clip around the bracket and lag bolted to each side of the power pole.

   Method 1 (through-bolt connection to the pole) has sufficient capacity to withstand the lateral forces in all earthquake zones. Method 2, which is usually found at older installations, could fail during an earthquake event if the safety chain is not present.

d. All electrical control panels should be properly anchored to avoid failure due to seismic activity. Although this paper attempts to present protection methods for primary equipment, secondary equipment protection may be required to avoid damage to nearby primary equipment. Electrical components such as control panels tend to be characteristic of relatively high centers of gravity, therefore upper restraint modes may be required as presented in Figure V-24.

e. Electrical Distribution System:

1. Electrical lines in electrical manholes should have sufficient cable slack to allow for movement without breakage. In all zones the cables in a manhole should be placed against the wall, supported on brackets of intervals to preclude sharp bends in the cables, and take the longest route between entrance and exit duct banks in order to provide slack in case of differential movement.

2. Parallel grid routing systems are recommended with a separation intended to reduce the chances of disrupting both routes simultaneously in case of a seismic disturbance, to improve the reliability of continuing energy supply to all critical elements of the treatment system.

3. Typical electrical distribution systems are characteristic of concrete-encased banks with some direct burial conduit from these banks into buildings. Experience in recent earthquakes, where concrete-encased duct banks have been broken, has indicated that not all electrical service has been interrrupted with a portion of power distribution maintained. Further, review of earthquake experience indicates that overhead wiring is generally satisfactory to withstand seismic forces. For all zones acceptable building entrance is via concrete encased duct

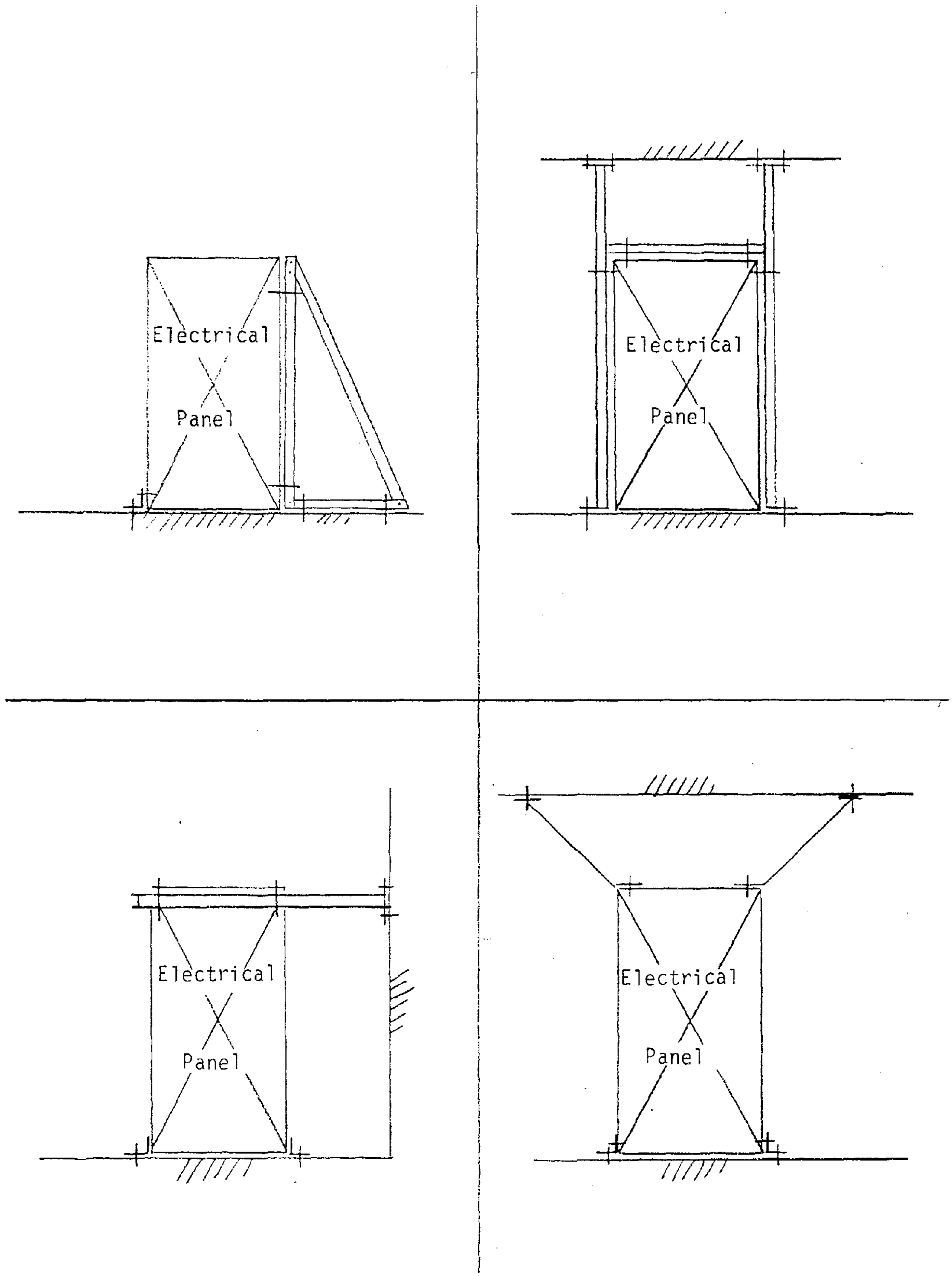


Figure V-24 Suggested Electrical Panel Restraint Systems. (68)

banks, or direct burial conduit from duct banks, passing through the exterior building wall below grade. Slack should be provided in cables when they enter a building or any rigid structure. At an overhead wiring entrance to a building adequate flexibility, to allow differential movement during a seismic disturbance, should be provided.

Emergency Power Systems

Examples:

a. Batteries
b. Secondary outside sources
c. Standby generators

Considerations:

a. Batteries mounted on the floor should be restrained to resist, shear and vertical forces. Restraining systems should be properly anchored to the floor. (See Figure V-25)
b. Batteries stored on a frame system with shelves required restraint of the support structure as well as the batteries, connection should be similar to that shown in Figure V-26.
c. Standby generators, if possible, should be rigidly anchored to the floor to resist seismic disturbances. If mounted on vibration isolators, scrubbers should be installed which will resist seismic forces.

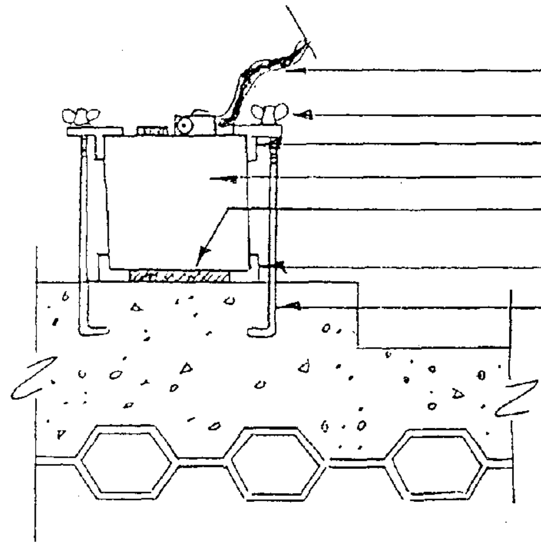


Figure V-25 Typical Battery Restraint System (71)

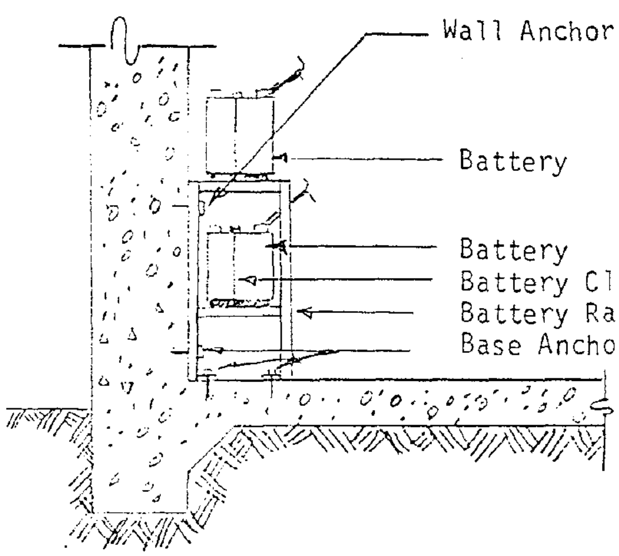


Figure V-26 Typical Emergency Power Supply Battery Set on Racks (71)

d. Fuel systems serving standby generators should be adequately protected against seismic damage. Flexible connectors should be provided, between the supply system and the engine. Figure V-27 depicts a typical fuel line system designed for flexibility. Consideration for the protection of fuel lines from falling debris is recommended.

e. Secondary or backup fuel supply systems should be considered. For example, electrically powered fuel pumps for filling the day tank may have a backup pump preferrably a manual type.

f. Flexible connections should be considered for the exhaust system serving the stand-by generator. A damaged generator system exhausting into an enclosed building can cause damage or injury to surrounding equipment and operating personnel. Figure V-28 presents a typical muffler installation including muffler supports and flexible joints.

g. Cooling water systems for the internal combustion engine unit of a generator should be a closed independent system such as a radiator/fan unit. The use of a water system to provide cooling is not recommended.

h. Typical generator unit include an internal combustion engine, coupled with an electric generator, with a radiator. All 3 components should be installed on one support frame as oposed to separate support systems for each component.

i. Secondary outside power systems should be independent from the main source of power to the plant. There should be no shared components between these systems.

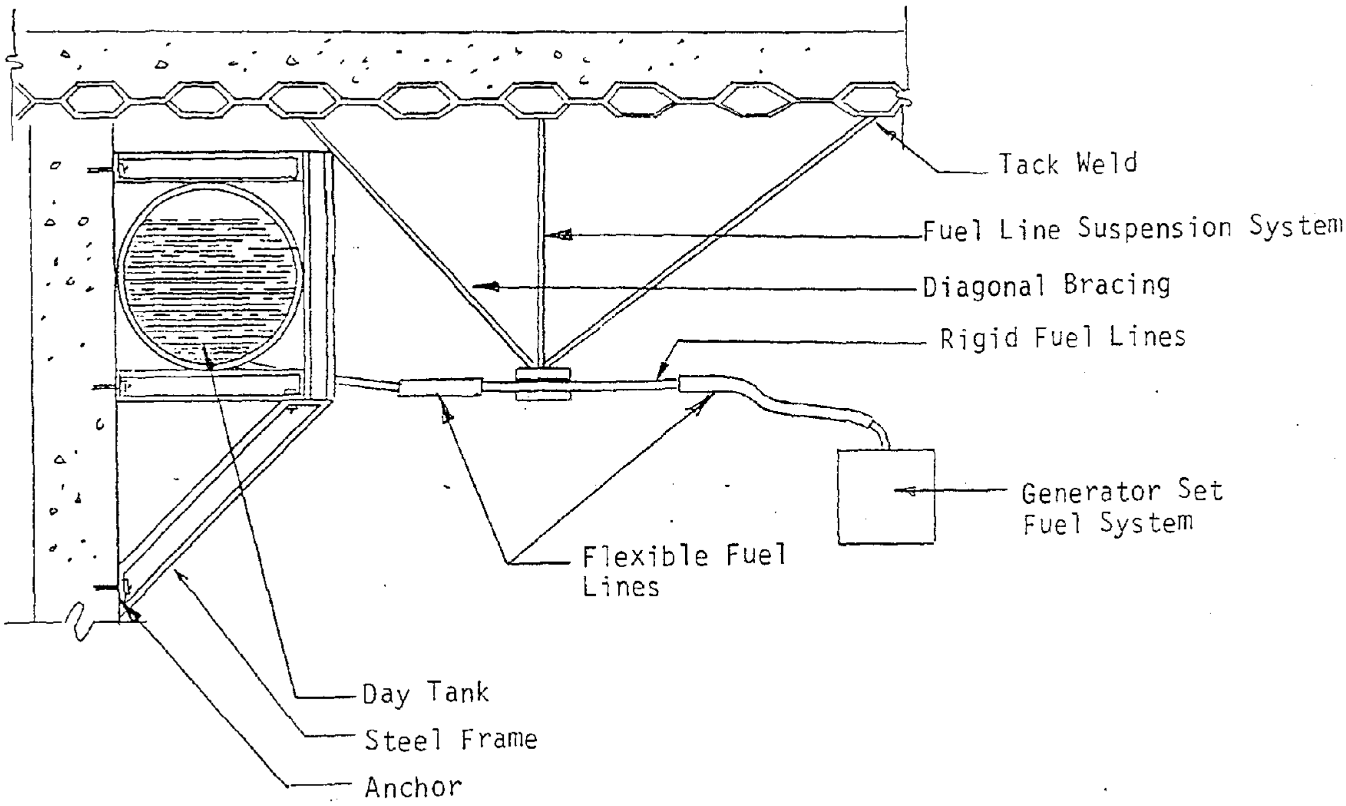


Figure V-27 Typical Day Tank and Flexible Fuel Line Support System (71)

j. Electrical cable installations in all situations should have sufficient cable slack incorporated to allow for equipment movement. (See Figure V-29).

Secondary Electrical Energy Systems

Examples:

a. Lighting systems

Considerations:

a. Although these systems are not classified as critical units for the continued operation of the treatment plant, their seismic restraint may be required for the following reasons:

   1. Protection of nearby primary systems which may be damaged by the failing secondary system.

   2. Protection of operating personnel who may be injured due to failing secondary systems.

b. Suspended light fixtures should be properly anchored to the ceiling to avoid falling during an earthquake event. The following description provides examples of typical installations of suspended light fixtures.

   1. Fluorescent lights: Typical units weigh 5 to 6 pounds per lineal foot and hang 30 inches below the ceiling on 3/8" 0 rod hangers. These fixtures are usually without safety chains. The hangers are attached by direct attachment to ceiling beams via nut on the 3/8" 0 rod above and below the beam flange or they are attached to a bent metal strap which is secured to the ceiling by two

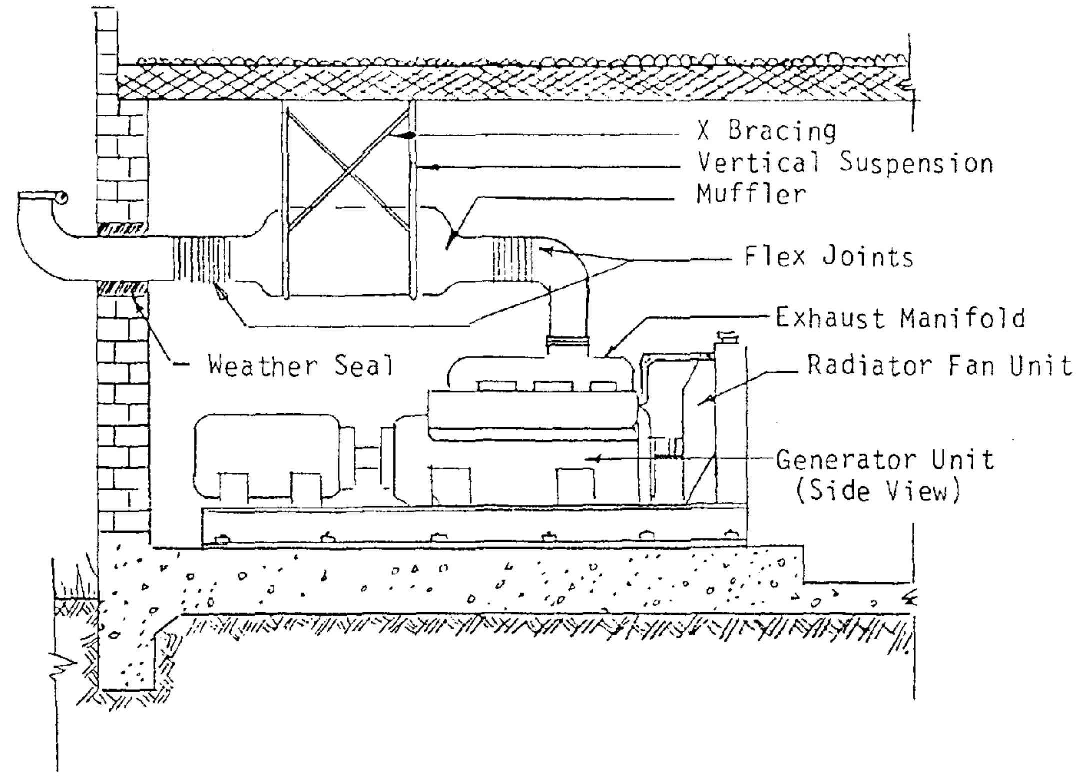


Figure V-28 Typical Flexible Muffler Exhaust System Installation (71

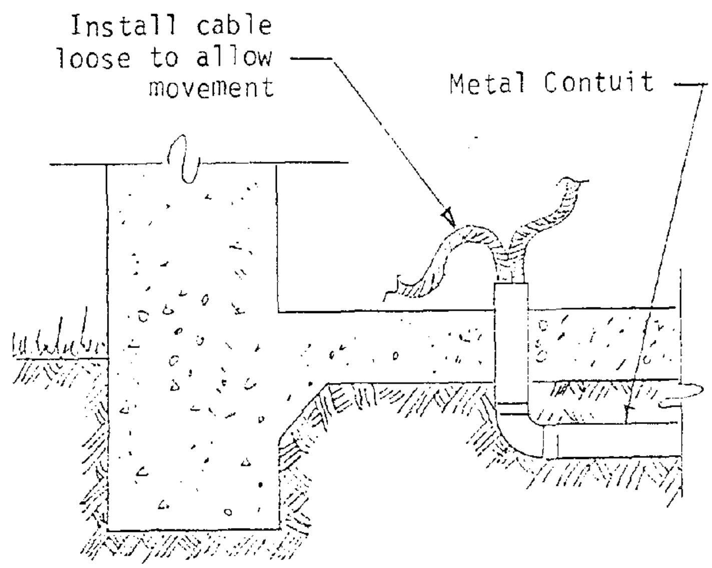


Figure V-29 Typical Electric Cable Installation (71) screws. Like the previous mode attachment, a nut on the 3/8" O rod above and below the bent metal strap provides a rigid connection at the top of the rod. Fixed rod bending stresses can be in excess of allowable stresses in both installation modes. Pull out of two screws in the ceiling has been the mode of failure in recent California earthquakes allowing the fiture to fall.

To prevent this, the lower nut should be removed or loosened from the hanger, thus, allowing the fixtures to pivot at the top of the hanger and swing freely. The upper nut must be provided with a locking device, such as a double nut, to prevent loosening. In addition, an arrangement of safety chains should be provided which is capable of supporting the fixture weight, attached from the light to the ceiling support system. Care must be exercised to be sure chain connections are independent from existing hanger rods. Indvidual fluorescent fixtures should be provided with a minimum of 2 safety chains located symetrically with the center of fixture mass and attached with eye bolts to the fixture and ceiling. Typical existing fixtures with recommended seismic modifications are shown in Figures V-30 and V-31.

2. Pendant mounted light fixtures: Older light fixtures are represented by a luminaire reflector assembly attached to a metal conduit which is attached to a ceiling plate. Upper connections are typically fixed, allowing for no free swing, while others have ball aligner connections allowing free swing

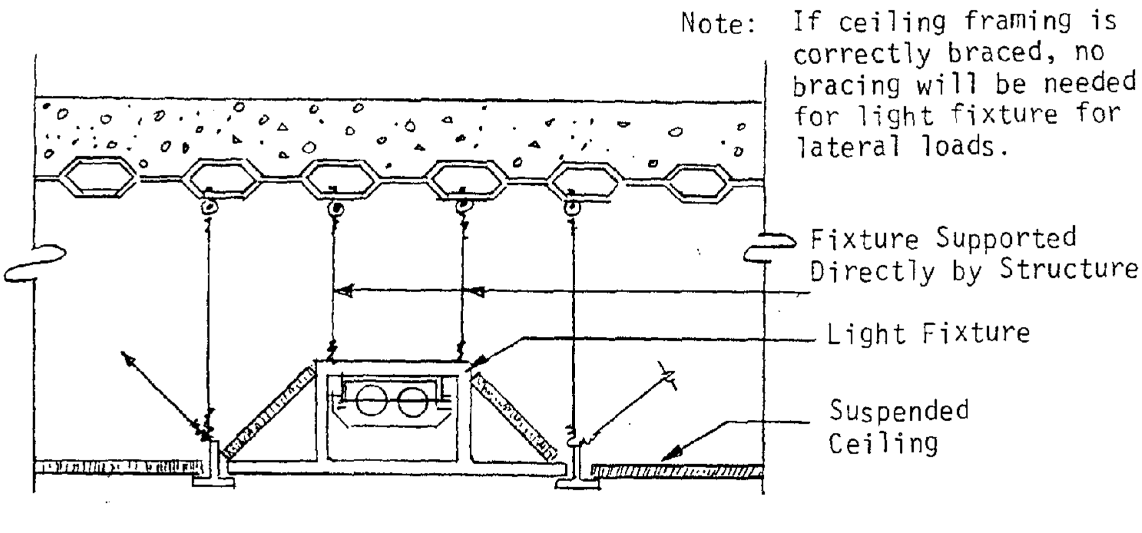


Figure V-30 Suspended Ceiling Lighting Fixture (71)

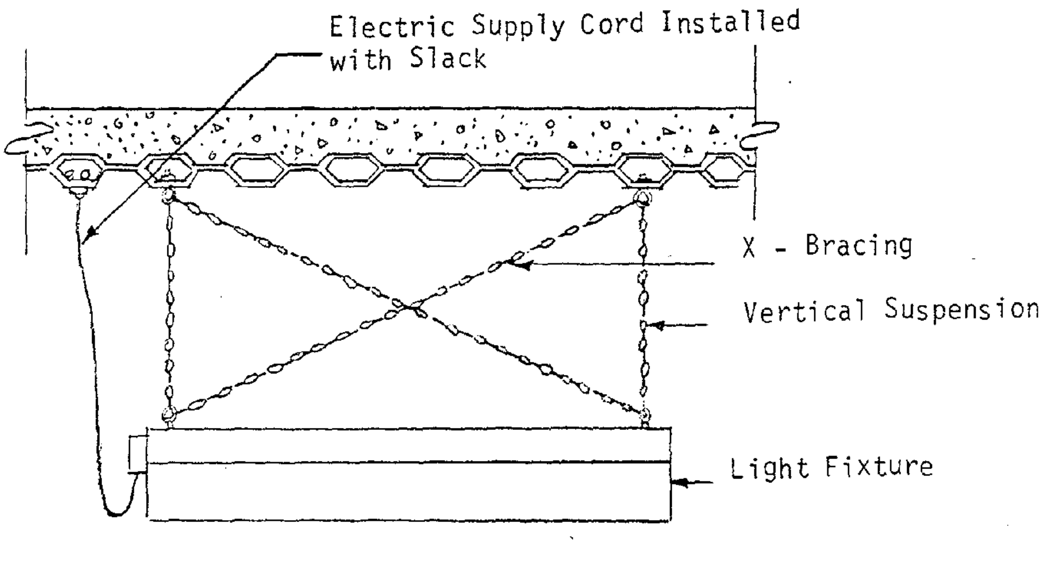


Figure V-31 Suspended Light Fixture (71) in any direction. Modification of the fixed connection by the loosening of the bottom nut at the top of the rod connection should be performed. Again, the upper nut should have locking device to prevent loosening. To prevent the fixture from falling, the addition of safety chains are recommended.

Immersed Equipment

Examples:

a. Air diffusers
b. Floating aerators and impellers of platform mounted aerators
c. Flocculator paddles/impellers
d. Mixer impellers
e. Launders/collection/distribution troughs
f. Overflow weirs
g. Sludge collectors
h Baffles
i Piping

Considerations:

a. The addition of seismically activated shut off switches should be considered for rotating submerged equipment that could be affected by wave action (e.g., flocculators, mixers, aerators, sludge collectors, etc.).

b. Provide break-away mountings (mechanical fuses) for equipment that cannot be designed to withstand seismic induced wave action (e.g., floating aerators, launders, baffles, etc.). This will allow "controlled" damage of the equipment, allowing damaged sections to be easily assessed and repaired. This type of system also aids in development of an equipment spare parts inventory for quick repair.

Specialized Structures

Examples:

a. Air compressor/storage tank units

b. Filter surface wash systems

c. Travelling bridge filter backwash systems

d. Travelling bridge sludge collectors

e. Conveyors

Considerations:

a. This class of equipment often includes complex structures, a detailed analysis of their seismic response is required utilizing standard seismic resistant design procedures.

b. Rigid anchorage is recommended for stationary items.

c. Systems supported on rails (e.g., travelling bridges, cranes and hoists) should be fitted with clips or other restraining devices to prevent them from "bouncing" of the track or rails.

d. Consideration should be given to providing a seismic activated shutoff switch for rotating equipment that may be damaged when operated during an earthquake.

Laboratories

Examples:

a. Laboratory equipment

b. Chemical storage

Considerations:

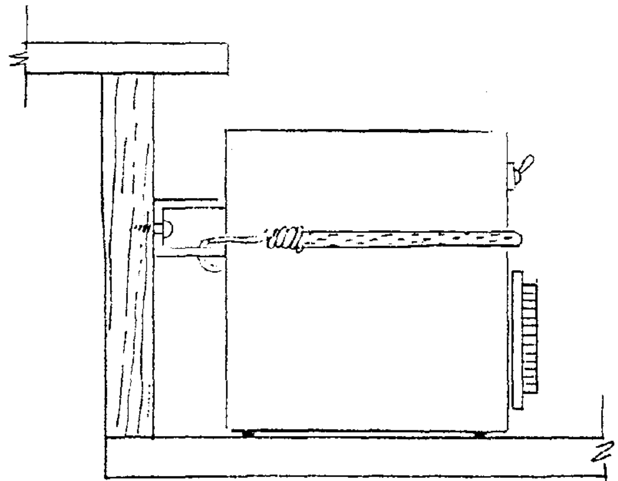
a. Table top equipment such as telephones and typewriters should be anchored or restrained so as to avoid movement during an earthquake.

b. Portable laboratory instruments and equipment should be anchored to avoid movement and toppling during an earthquake event (See Figure V-32).

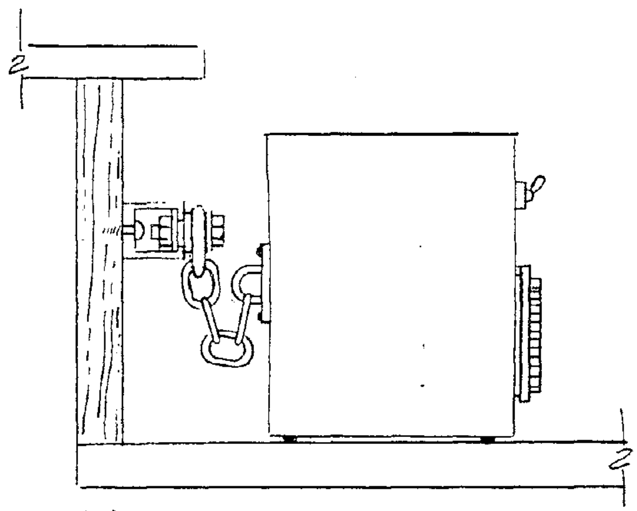
c. Laboratory countertips should have a raised outer edge lips for spill containment.

d. Office and laboratory shelving should have restraining methods incorporated which will keep stored items on the shelves during seismic activity. Figure V-33 presents typical shelved item retaining methods.

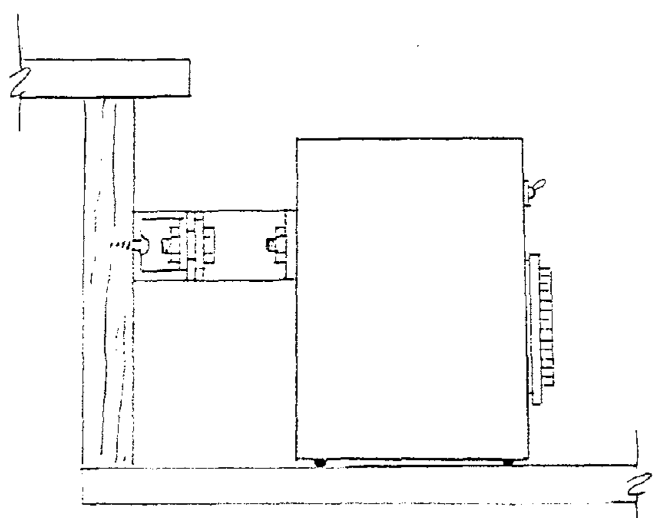
e. Chemical storage facilities and glassware storage facilities such as shelves and cabinets should be adequately anchored to hinder overturning. Shelves should have an item retainer system to avoid the falling of shelved items. Cabinet doors should have a positive latching system to keep doors closed during seismic activity. Magnetic or push/pull latching systems should be removed or altered.



(a) Elastic Strap to Front of Equipment



(b) Flexible Equipment



(c) Rigid Attachment

Figure V-32 Typical Counter Top Equipment Attachment Systems (71)

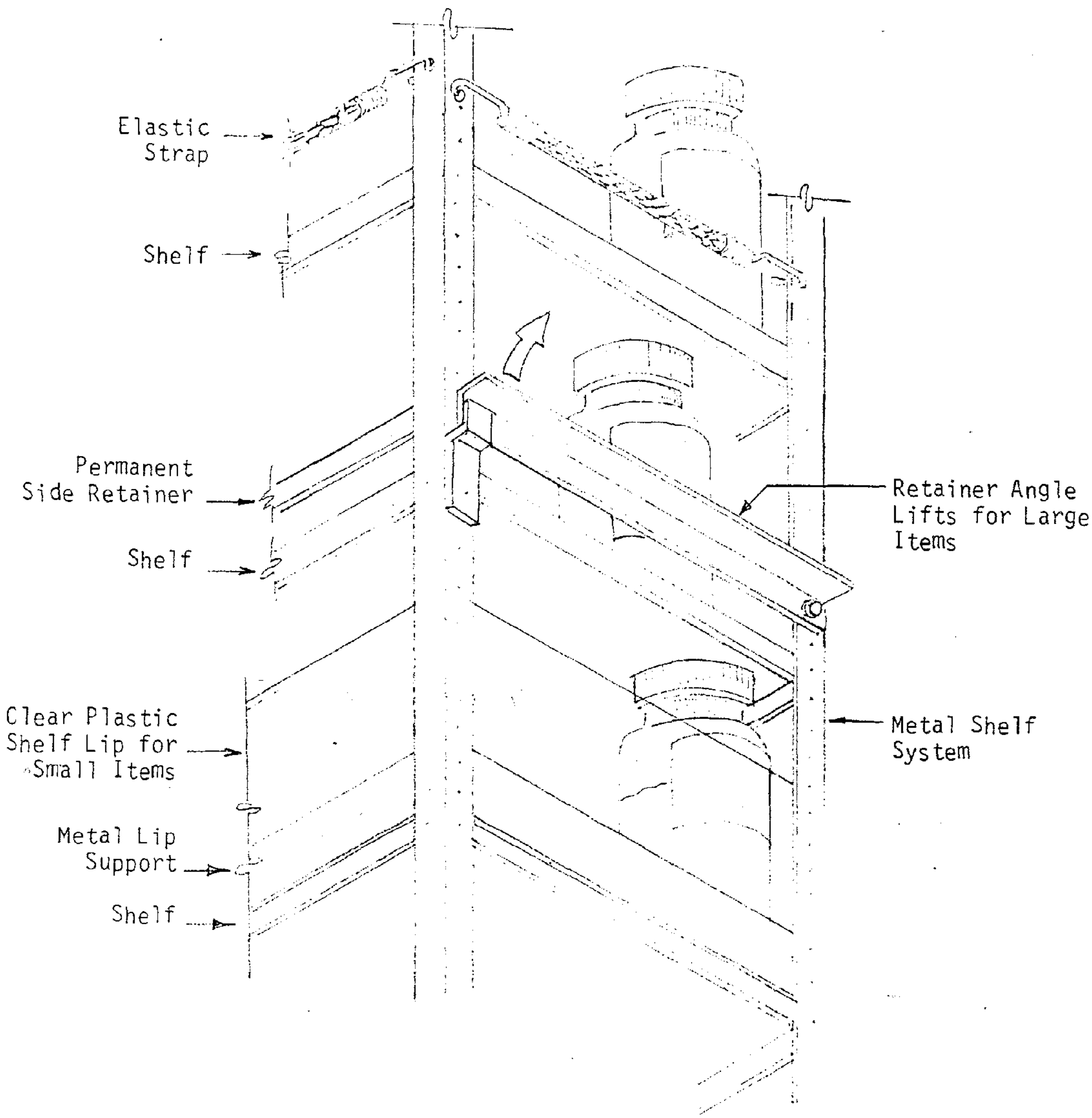


Figure V-33 Typical Shelved Item Retainer Systems. (71)

f. It is recommended that all concentrated acids and other caustic chemicals be stored in their shipping cartons until use. This system of storage will hinder container breakage due to impact during seismic activity.

g. Large plate glass windows can cause considerable equipment damage and personnel injury due to breakage during earthquake activity. All large plate glass windows should be replaced with safety type plate glass or wire mesh reinforced glass.

Chapter VI

Cost Analysis and Retrofit Feasibility

Purpose

The purpose of a cost analysis of a retrofit program is to determine the feasibility of implementing such a program. A preliminary cost analysis will aid municipal officials in the planning and evaluations of proposed seismic retrofit programs as follows:

- combined with risk analysis, financing costs and estimates of the expected life of the existing facilities the preliminary costs can be used to determine the economic feasibility of the project as a whole

- assist in the determination of the most economical engineering solution by comparing alternative solutions

- to determine the level of retrofitting achievable within a given budget that will ultimately achieve minimum system performance standards

- aid in establishing a budget/capital improvement plan for future design and construction

Background

A preliminary cost analysis should be conducted after the system has been evaluated according to the principles of functional and vulnerability analyses as previously discussed. These evaluations will result in an itemized list of systems and/or components that must be modified in order to maintain a specified level of service from the water supply system after a moderate to severe earthquake.

From the data collected to this point in the system evaluation phase, personnel experienced in seismic retrofit techniques can specify preliminary, rough estimates of the level of retrofitting required and the types of construction techniques generally available to achieve integrity of the critical components. Costs associated with the major projects indicated in the preliminary analyses can be roughly estimated from experience, often based upon gross estimates of the amounts of additional pipe line required, yards of concrete required, number of valves to be placed and the extent of equipment tie-downs and/or equipment replacement required. From such rough estimates, a range of magnitude of retrofit program costs can be estimated. This information will aid in determining the feasibility of implementing the seismic retrofit program and the decision can be made whether or not to proceed with further structural analysis and more detailed cost estimates.

The categories of work to be considered in a seismic retrofitting program will generally fall into the following broad categories:

- Demolition/access costs - This category includes the removal of structures or supports to be replaced, the removal of architectural and structural items for access to the item being retrofitted, the disposal of non-reuseable material, dismantling equipment that is either in the way of actual retrofitting work or poses a hazard to critical facilities.

- Reconstruction Costs - Includes the placement of concrete, steel or other material for structural or architectural integrity as required for seismic resistance. Also includes the relocation of equipment that was displaced during the demolition phase. This category also includes the placement of new equipment required for seismic resistance such as snubbers, valves, etc. but does not include the cost of these items.

- Mechanical and Electrical Work Costs - Cost for rerouting concealed or surface mechanical and electrical systems where required by the retrofit work. Includes the relocation of pipes, conduit, ducts, etc. associated with the water sypply system or support systems.

- Equipment Costs - Includes the cost of new equipment required for the retrofit projects such as the snubbers, valves, etc. These costs should also include items needed for inventory purposes such as replacement parts, emergency response equipment, etc. determined to be an integral part of either the seismic system or the post-seismic event response.

o Finishing Costs - Work needed to return the building/equipment to its original condition. This may include concrete patching, painting, roofing, tiles, etc. This category is not generally a large percentage of project costs but should be included if it can be reasonably ascertained.

Remedial work or retrofitting generally does not lend itself to 'handbook' pricing. This fact is due to the variety of conditions encountered when conducting this type of work. Often 'on the spot' decisions and/or change orders need to be addressed that could not be forseen before construction began. Therefore retrofitting work requires more coordination and supervision than does new construction. Costs based upon previous similar projects are generally satisfactory for preliminary cost estimates since they incorporate principles of aseismic construction practice. However, caution must be used when costs estimates from previous retrofitting programs are used to project preliminary cost figures for a proposed project. Care must be taken to assure the projects being compared are truely comparable in labor, materials and equipment required. Even when experienced engineering judgement determines the jobs to be essentially equivalent, varations in costs will occur due to factors such as locality, productivity, and contingencies which will be specific to the individual projects. Costs will also vary with the amount of repetitive operations versus isolated or unique operations. Generally high quantity work items will tend to reduce costs. The complexity of developing preliminary cost estimates requires the expertise of experienced engineering judgement familiar with construction practices and pricing of remedial work.

Decision Analysis

Decision analysis is the tool by which the feasibility of implementing an aseismic retrofit program is evaluated. Decision analysis can occur at various stages within the program evaluation process depending upon the extent of information needed to evaluate the feasibility of a program. For example, a preliminary evaluation may be sufficient to determine that retrofitting a water supply system is not feasible. A decision not to retrofit may be made at this level based upon any of the following factors:

- The risk of a damaging earthquake is extremely remote and the probability of an event within the life of the water supply system is negligable.

- The facilities have recently been designed and built under strict aseismic code provisions and shows no evidence of deterioration or irregularities with building code requirements or state-of-the-art design standards regarding aseismic design.

- The water supply system is determined to be extensively vulnerable and at very high risk of experiencing a devastating earthquake. Experience indicates a retrofitting program to be economically infeasible. This situation may ocur when the facilities have been located on sites with special hazards such as soil failure and/or when construction techniques indicate extensive replacement would be required.

- The water supply facilities may be near the end of their useful life and therefore replacement with aseismically designed facilities rather than retrofitting would be appropriate. This may be true for only a portion of the facilities (i.e., the filtration plant) while the other facilities (intake, distribution, storage, etc.) may have additional useful life. Therefore this criteria for not retrofitting may be applicable to only some sections of the water supply facilities. The portions of the system planned for continued use will require more in depth evaluation.

If however, a preliminary evaluation of the water supply system does not preclude the need for a retrofit program a more detailed evaluation must be conducted. A cost-benefit analysis of a retrofit program is required. The first step of a cost-benefit analysis is an estimation of the costs resulting from water system damage by expected seismic activity. In order to simplify the process of damage estimation, the damages must be classified according to the type, cause and the sub-system of the water supply system in which they are incurred. The following costs can be associated with seismic damage of water supplies.

- repair costs
- replacement costs
- indirect economic losses (industry, business interuptions)
- socio-economic loss
- emergency water supply costs
- Health and mortality costs
- Revenue loss to the utility (interuption of service)

As indicated previously losses are categorized as either direct or indirect. Direct losses include the cost of repair, replacement, cost of emergency operations (e.g., water supply lines, etc.) water deliveries, etc. Indirect costs such as fire loss, loss of life and industry and business disruptions are much more difficult to quantify and at times become very controversial.

Earthquakes of major magnitude in the U.S. are relatively rare with many years between events. This circumstance has resulted in there not being a valid record of the extent of losses or costs due to various sizes of magnitudes of earthquakes. The San Francisco fire of 1906 causesed extensive fire damage and loss of human life. Subsequent earthquakes have not experienced this level of damage. Reasons for this are numerous, but a major contributing factor is that building codes have changed since the turn of the century and this type or extent of damage is not likely to occur.

Indirect losses will be difficult to determine without careful modelling of the specific water supply system, the various sectors of the economy, and susceptibility of these areas to economic loss due to interruption of the water supply. Often these determinations by necessity are subjective and open for debate, for example, human life is difficult to put a price on, however, this type of analysis will generally require an analytical approach. Therefore indirect cost can exceed direct costs of an earthquake by many factors.

The complexity of cost analysis for a water supply system is much greater than that for the analysis of a simple building or structure. The literature is replete with examples and evaluations of the cost considerations for retrofitting a building. These costs generally relate to the (1) direct costs: retrofitting cost vs. replacement cost and (2) indirect costs: building use and occupancy. Water lifeline costs/benefit analyses are much greater ramifications than single buildings or structures. This situation is complicated further by the geographic extent of the water supply systems and the fact that single magnitude or intensity earthquakes (design level) can not be applied to the water lifeline system as a whole as is possible with most buildings.

Therefore the development of a conventional cost-benefit analysis may be extremely difficult to accurately address. Other contributing complications involves the following:

- o Seismic experts are not capable of predicting with any degree of certainly the frequency location or magnitude of future earthquakes

- The data base on earthquake damage to modern facilities is not extensive enough to predict potential damage to all systems from direct seismic impacts.

- There is no means in which to predict numbers of fires or their extent after an earthquake.

Efforts have however been made to estimate losses and costs to water supply systems (73, 74, 75). These studies have generally been site specific and involve detailed seismic risk analysis with many assumptions and generalizations. These analyses generally incorporate probabalistic data with respect to the peak ground acceleration and potential failure of a water supply system, subsystem or component.

Two types of decision tools are generally used on these economic analyses, they are the "minmax" rule and the "expected value" rule. The "expected value" rule seems to be particularly applicable to the probability of extreme events such as earthquakes. This type of analysis is frequently used in the evaluation of expected damages associated with other natural disasters such as floods. This method of cost analysis is particularly adaptable to evaluating the cost of extreme events where the extent of damage is a function of the magnitude of the event. This certainly exists with respect to earthquakes and water supply system damage. For the expected value of loss is to be solved quanitatively rather than by someones guess, estimates must be made of:

1. The expected frequency and magnitude of future earthquakes.

2. The extent of damage and the consequences of the expected earthquake(s).

3. The money outlays (both immediate investment and subsequent disbursements) to make modifications to reduce the risk of damage to the water supply system.

4. Any other direct or indirect costs assocaited with the occurrance of an expected earthquake.

The practical difficulty lies in evaluating these items as in the previous discussion of cost benefit analysis. It is generally easy to recognize cases in which it clearly pays to reduce risks because the cost of retrofitting is small, and the prospective damage due to an earthquake are large (e.g., adding anchor bolts to critical equipment such as motors, pumps, etc.). Similarly, it is easy to recognize cases at the other extreme where costs of retrofitting is high and the risk of an earthquake is very slight (e.g., retrofitting an intake structure in a low seismic area). But it is usually not possible to make a quantitative approach to those many situations where the absence of data or reliable information on the frequencies of earthquakes and the amount of damage that will occur can not be identified. Generalized data of this type will require an extensive world-wide assessment of seismic related damage as is presently being pursued by various seismic science and engineering organizations. However, the controversy over the extent of indirect costs of seismic events will still be difficult to quanitatively account for in the development of retrofit decision analyses.

Conclusions

Cost analysis for justification of the extent of a retrofit program for a water supply system can not be made solely on the basis of quantitative information. There are too many unknown variables with respect to earthquake frequency and magnitude of any specific site as well as unknown consequences of seismic activity. Therefore quantitative and subjective information must be developed from "best engineering judgement" by experts in the field of water lifeline engineering. This information may be used to develop seismic risk models for the evaluation of specific water supply systems.

The cost analysis will be greatly influenced by the estimate of the return frequency of an earthquake of damaging magnitude. In seismic zones 0-2 the projected probability of a damaging earthquake (MM 7) is so small that all other factors with respect to expected damage are minimized. It therefore becomes evident that existing water supply systems in these zones can not justify major retrofit programs. However, small expenses for anchoring major equipment may be desirable in areas adjacent to zone 3 areas, since the graphical demarcations between zones are not significant.

Zones 3 and 4 will require more detailed analysis to determine the feasibility of a retrofit program and also to provide justification for the level or extent of a retrofit program in these areas, it will be required to conduct a detailed functional evaluation of the water supply system and identify those areas which are highly vulnerable to seismic forces. Detailed cost estimates will need to be developed for the systems identified as requiring retrofit measures. Below are cost categories for typical areas required for seismic retrofitting of a water supply system.

1. Heavy equipment tie down
    a. Bolts
    b. Welding and bolts
    c. Snubbers, vibration isolators
2. Pipe placement (bypass)
3. Valve installation
4. Pipe through wall
5. Pipe anchors (suspended, ceiling)
6. Pipe hangers (wall)
7. Equipment hangers (ducts and heaters)
8. Transformer restraint to pole
9. Light restraints, (minimum 2 chains)
10. Tank wall stiffeners
11. Pneumatic lock out device
12. Increase electrical wire slack
13. Chlorine tank tie downs
14. Lab equipment tie downs
15. Piping installations
    a. Mechanical joints
    b. Sleeve joints
    c. Ball joints
    d. Anchor rods at elbows and joints
    e. Flexible rubber bellows
16. Electrical panel supports

It is apparent that the identification of retrofit needs at a facility requiring extensive improvements will need to prioritize and schedule improvements over several years. Few municipalities have the resources to adopt a program of this type in total. Therefore it will be necessary for a strategy to be developed to retrofit those items listed as the most critical and vulnerable first and schedule the lower priority items for later work. Large or detailed retrofit requirements may be quite expensive and need to be placed in the capital improvements plan for the water utility, in this case scheduling of design and construction activities will need to coincide with the availability of resources.

Smaller projects such as those requiring installation of anchor bolts or vibration isolator snubbers will usually be able to be conducted by the utility maintenance personnel. This has the advantage of being an in-house project that can be conducted for little more cost than the hardware required to perform the retrofit. These small projects can be conducted quickly and are frequently capable of greatly improving the seismic resistance of critical components.

In summary, the feasibility of retrofitting a water supply system against seismic forces is dependent on the probability of a damaging earthquake, the useful life of the water system, the cost expected to be incurred if a damaging earthquake occurs, and the availability of resources to develop, design and implement an appropriate program. These variables are site and system specific and require evaluation by qualified seismic experts.

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