DESIGN GUIDELINE FOR SEISMIC RESISTANT WATER PIPELINE INSTALLATIONS

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ABSTRACT

Seismic design for water pipelines is not explicitly included in current AWWA standards. Compounding this problem, standard water pipeline materials and installation techniques are prone to high damage rates whenever there is significant permanent ground deformations or excessively high levels of ground shaking.

To help improve this situation, a new Design Guideline for Seismic Resistant Water Pipeline Installations (the Guidelines) has been developed. It is intended that the Guidelines be issued in March 2005. For the period from November 2004 through January 2005, the Guidelines are available in draft form for public comment. Comments from U.S., Japanese, Canadian and all other water utilities, pipeline manufacturers, AWWA, JWWA and other interested parties are welcomed.

The Guidelines provide direction for three situations:

- When the pipeline engineer has just rough estimates of the earthquake hazard, does not have the resources to do design by analysis, and wishes to rely on standardized pipeline components. The Guidelines provide the Chart Method. This is the preferred approach for common pipeline installations like 6-inch to 8-inch diameter pipes, fire hydrants and service laterals.

- When the pipeline engineer wishes to perform a limited design by analysis. The Guidelines provide the Equivalent Static Method. This is the preferred approach for medium important pipelines like 12-inch to 24-inch installations, or as a preliminary approach for major transmission pipelines.

- When the pipeline engineer has the resources to perform detailed subsurface investigations, geotechnical engineering and pipe stress analyses. The Guidelines provide the Finite Element Method. This is the preferred approach for essential non-redundant installations, like 36-inch to 120-inch pipelines.

INTRODUCTION

In most every severe earthquake, the largest negative impact to water utilities has been the damage to buried water pipelines. At the past three JWWA-AWWARF workshops (Oakland

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2000, Tokyo 2001, Los Angeles 2003), a great emphasis was placed by many participants on the rate of pipe damage, the causes of pipe damage, and the improved earthquake performance of new types of pipe.

After the Los Angeles workshop, many US participants got together and decided something ought to be done about this. Accordingly, in concert with FEMA, NIBS and the ALA, a team of engineers was assembled to put together the first ever US seismic design guideline for buried water pipelines. The American Lifelines Alliance (ALA) was formed by the Federal Emergency Management Agency (FEMA) in 1998 as a public-private partnership whose goal is to reduce risk to utility and transportation systems from natural hazards and manmade threats. In 2002, FEMA contracted with the National Institute of Building Sciences (NIBS) through its Multihazard Mitigation Council (MMC) to, among other things, assist FEMA in developing these Guidelines. The ALA sponsors this work through funding from NIBS and FEMA.

AmericanLifelinesAlliance

AUTHORS

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The Guidelines would not have been possible without the contributions from numerous staff of the San Francisco Public Utilities Commission, East Bay Municipal Utilities District, City of San Diego Water Department, the Los Angeles Department of Water and Power, and many other participating agencies.

OUTLINE OF THE GUIDELINES

The Guidelines describe the various steps in seismic water pipeline design, with commentary. The main topics included are: Goals; Performance Objectives; Earthquake Hazards; Subsurface Investigations; General Pipeline Design; Analytical Models; Transmission Pipelines; Bypass Pipelines; Distribution Pipelines; Service and Hydrant Laterals; Distribution Pipelines; and Other Components. The Guidelines are meant to be a self-standing document that can be used by pipeline designers in water utilities; as such, it is geared to provide simple procedures to achieve the overall goal. The Guidelines always allow for more detailed procedures to be used by geologists, geotechnical engineers and pipeline engineers when suitable. A link to obtain the entire draft Guidelines is listed in the Conclusions.

For the 4th AWWARF-JWWA workshop, four papers cover the major topic areas of the Guidelines. This paper describes performance goals and the design-by-chart method. The paper by Dr. Craig Davis covers reliability goals and definition of geotechnical hazards. The paper by Mr. Luke Cheng covers design issues for transmission pipelines. The paper by Mr. Bruce Maison covers the two design-by-analysis models and design issues for service laterals.

GOAL OF SEISMIC DESIGN FOR WATER PIPELINES

The goal of the Guidelines is to improve the capability of water pipelines to function and operate during and following design earthquakes for life safety and economic reasons. This is accomplished using a performance based design methodology that provides cost-effective solutions and alternatives to problems resulting from seismic hazards. Improved water pipeline performance will help create a more resilient community for post-earthquake recovery; therefore portions of the Guidelines inherently consider the community impacts if pipeline damage were to occur. The Guidelines do not intend to prevent all pipelines from being damaged.

To achieve this goal, the fundamental intent of the Guidelines is to assure a reasonably low rate of water pipeline damage throughout a water utility system, such that about 90% of customers in a system can be restored with piped water service within about three days after a design basis earthquake.

To achieve this level of performance, an acceptable damage rate will be about 0.03 to 0.06 breaks per 1,000 feet (0.1 to 0.2 breaks per kilometer) of equivalent 6-inch diameter pipe. The commentary of the Guidelines provides a calculation to convert a network of pipes of different diameters that may suffer both breaks and leaks, in conjunction with network redundancy, into a single equivalent break rate per equivalent 6-inch diameter pipe. By minimizing pipeline damage after earthquakes to this level of damage, a typical water utility serving a population of 150,000 people could expect to:

- Deliver water at serviceable pressure to 65% to 90% of all hydrants within the first hours after the earthquake, as long as there are adequate supply sources; and
- Deliver water via the pipe network to at least 90% of all customers within 3 days following an earthquake;

as long as the utility can isolate most of the leaking and broken pipes within one day or so, and repair equivalent 6-inch diameter pipes at a rate of about 20 within the first three days after the earthquake, and 20 per day thereafter.

For water utilities with limited post-earthquake repair capability, or serving pipe networks with limited or no redundancy, it is important to limit the damage rate to the lower range. For water utilities with much greater post-earthquake repair capability, it might be acceptable to sustain damage to the higher range.

NEW INSTALLATIONS AND REPLACEMENT / RETROFIT

It is the intent of the Guidelines that they be used for all new pipeline installations. Over a period of many years, a sufficiently high percentage of pipelines in a network will eventually have been designed per these Guidelines. Thus, it may take decades for some utilities to ultimately achieve the goals, unless a pipeline replacement / retrofit program is also adopted.

The decision to replace older pipes is a complex one. In many networks, many existing pipelines (such as cast iron pipe with caulked joints) will not meet the seismic design capability recommended by the Guidelines. Still, the Guidelines do not recommend replacing older 4-inch to 10-inch diameter cast iron pipes solely on the basis of earthquake improvement, since this is not thought to be cost effective. However, as old pipeline are thought to need replacement because they no longer provide adequate fire flows, or have been observed to require repair at a rate of more than once every 5 years, then the added benefit of improved seismic performance may justify pipe replacement. When replaced, the new pipes should be designed per the Guidelines.

Replacement of larger diameter pipelines (12-inch diameter and upwards) may be cost effective just from a seismic point of view, in areas prone to PGDs.

PIPELINE FUNCTION CLASSES

A pipeline's function within the system identifies its importance in achieving the system performance goal. Table 1 provides the 4 function classes. A pipe function identifies a performance objective of an individual pipe, but not that of an entire system.

Function	Seismic Importance	Description
I	Very Low to None	Pipelines that represent very low hazard to human life in the event of failure. Not needed for post earthquake system performance, response, or recovery. Widespread damage resulting in long restoration times (weeks or longer) will not materially harm the economic well being of the community.
II	Ordinary, Normal	Normal and ordinary pipeline use, common pipelines in most water systems. All pipes not identified as Function I, III, or IV.
III	Critical	Critical pipelines and appurtenances serving large numbers of customers and present significant economic impact to the community or a substantial hazard to human life and property in the event of failure.
IV	Essential	Essential pipelines required for post-earthquake response and recovery and intended to remain functional and operational during and following a design earthquake.

Table 1. Pipe Function Classifications

THREE DESIGN APPROACHES

The Guidelines provide three approaches can be used in the design of buried pipelines.

- Chart method. The simplest approach. Avoids all mathematical models, and allows the designed to pick a style of pipe installation based on parameters such as regional maps for PGV and PGD hazards, and the pipeline function class.

- Equivalent static method. Uses simple quantifiable models to predict the amount of stress, strain and displacement on a pipe for a particular level of earthquake loading. The pipeline can then be designed to meet these quantified values, or pipe styles can be selected that presumably meet these quantified values without a formal capacity to demand check. Pipe selection is usually made by specification from available manufacturer's catalogs.

- Finite element method. This method uses finite element models to examine the seismic loads (whether PGA, PGV or PGD) over the length of the pipeline, and then uses beam on inelastic foundation finite element models (or sometimes use two- or three-dimensional mesh models) to examine the state of stress and strain and displacement within the pipeline and pipeline joints. Pipe design is often shown on contract drawings, covering material selection, joint preparation, trench design and other factors.

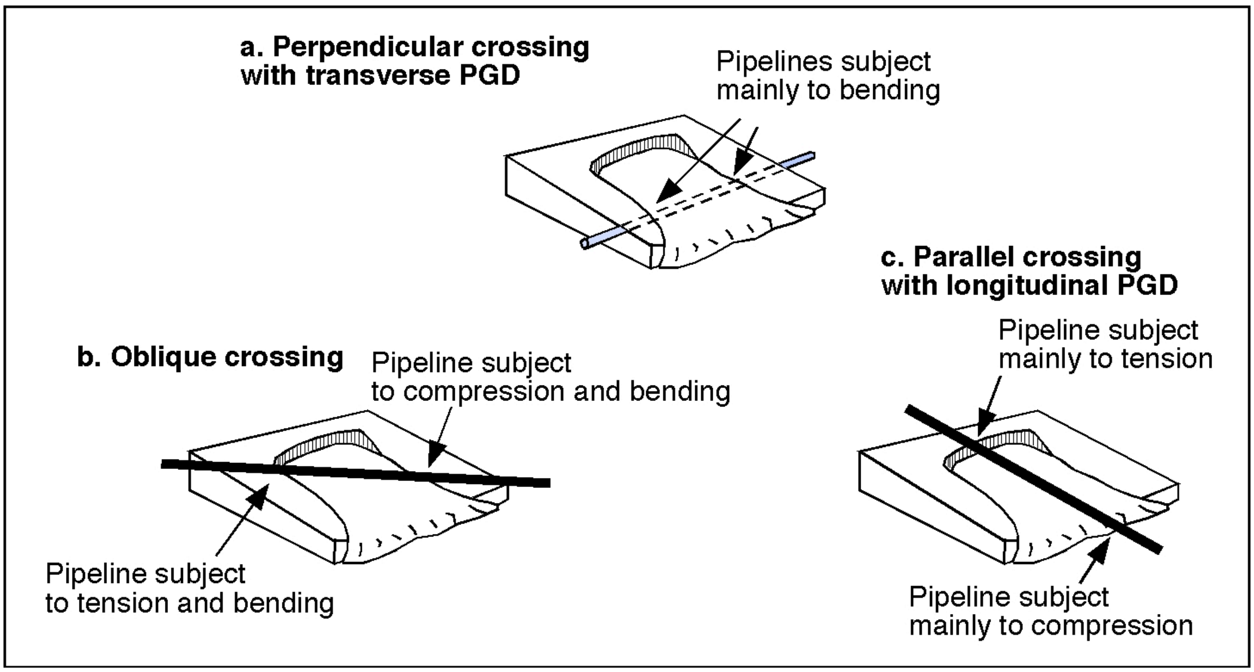


Figure 1. Direction of Permanent Ground Deformation (PGD)

CHART METHOD

Transmission Pipelines

Transmission pipelines may carry raw or treated water. Due to their importance to a great number of people, Function Class I is generally to be avoided except for those pipes whose failure would not impact any customer for 30 days or more.

Tables 2 to 5 set the pipeline design category (A, B, C, D or E). Figure 1 shows the meaning of perpendicular (transverse) and parallel (along the axis) orientations. If a portion of a pipeline has two or more categories for the various hazards (ground shaking, transverse PGDs, parallel PGDs, fault offset PGDs), then the highest category controls.

Inch/sec	Function I	Function II	Function III	Function IV
0 < PGV ≤ 10	A	A	A	A
10 < PGV ≤ 20	A	A	A	B
20 < PGV ≤ 30	A	A	B	C
30 < PGV	A	B	C	D

Table 2. Transmission Pipelines – Ground Shaking

Inches	Function I	Function II	Function III	Function IV
0 < PGD ≤ 2	A	A	A	A – welded steel B - segmented
2 < PGD ≤ 6	A	A	A	B
6 < PGD ≤ 12	A	A	B	C
12 < PGD	A	B	C	D

Table 3. Transmission Pipelines – Liquefaction and Landslide Transverse to Pipeline Alignment

Inches	Function I	Function II	Function III	Function IV
0 < PGD ≤ 2	A	A	B	B
2 < PGD ≤ 6	A	B	B	C
6 < PGD ≤ 12	C	C	C	D
12 < PGD	D	D	D	E

Table 4. Transmission Pipelines – Liquefaction (Lateral Spread) and Landslide Along Axis of Pipeline

Inches	Function I	Function II	Function III	Function IV
0 < PGD ≤ 2	A	A	B	B
2 < PGD ≤ 6	A	B	B	C
6 < PGD ≤ 12	A	C	C	D
12 < PGD ≤ 24	A	D	D	E
24 < PGD	A	D	E	E

Table 5. Transmission Pipelines – Fault Offset

Distribution Pipelines, Service Laterals and Fire Hydrant Laterals

In most cases, distribution pipelines are in networks. Failure of a single distribution pipeline will not fail the entire network (once the broken pipe is valved out), but the customers on the broken distribution pipeline will have no piped water service until the pipe is repaired. The engineer can assume that distribution pipelines are Function Class II, except in the following cases:

- The pipeline is the only pipe between lower elevation pump station and upper elevation pump station / reservoir in a pressure zone, and the failure of that pipeline will lead to complete loss of supply to the pump station serving a higher zone, or loss of the water in the reservoir for fire fighting purposes. For example, a 12-inch diameter pipe from lower elevation pump station that delivers water to a higher elevation tank within a pressure zone, and that also serves water to higher elevation pump stations.

- The pipeline is the only pipe delivering water to particularly important customers, such as critical care hospitals. For example, an 8-inch diameter pipe that has a service connection to a 200 bed hospital.

Past earthquakes have shown that there can be great quantity of damage to distribution pipelines, especially in areas prone to PGDs or high velocity pulses. While no single distribution pipeline is as important as a transmission pipeline, the large quantity of distribution pipe damage can lead to rapid system-wide depressurization, loss of fire fighting capability, and long outage times due to the great amount of repair work needed. Accordingly, we recommend that most distribution pipes be classified as Function Class II and very few as Function Class I (under ~5% of total pipeline inventory). A few distribution pipes serving essential facilities could be classified as Function III or IV; or they could be designated in suitable emergency response plans as prioritized for prioritized and rapid repair (generally under one day or two days at most). Once the Function Class is set, Tables 6 to 11 define the Design Category.

Inch/sec	Function I	Function II	Function III, IV
$0 < PGV \leq 10$	A	A	A
$10 < PGV \leq 20$	A	A	A
$20 < PGV \leq 30$	A	A	A (with additional valves)
$30 < PGV$	A	A (with additional valves)	B

Table 6. Distribution Pipelines – Ground Shaking

Inches	Function I	Function II	Function III, IV
$0 < PGD \leq 2$	A	A	A (with additional valves)
$2 < PGD \leq 6$	A	A (with additional valves)	B
$6 < PGD \leq 12$	A	B	C
$12 < PGD$	A	C	C

Table 7. Distribution Pipelines – Liquefaction and Landslide Transverse to Pipeline Alignment

Inches	Function I	Function II	Function III, IV
0 < PGD ≤ 2	A	A	B (with additional valves)
2 < PGD ≤ 6	A	B	C
6 < PGD ≤ 12	A	C	D
12 < PGD	A	D	D

Table 8. Distribution Pipelines – Lateral Spread and Landslide Along Axis of Pipeline

Inches	Function I	Function II	Function III, IV
0 < PGD ≤ 2	A	B	B
2 < PGD ≤ 6	A	B	C
6 < PGD ≤ 12	A	C	D
12 < PGD ≤ 24	A	D	E
24 < PGD	A	E	E

Table 9. Distribution Pipelines – Fault Offset

Service Laterals and Hydrant Laterals

Inch/sec	Any Lateral
0 < PGV ≤ 10	A
10 < PGV ≤ 30	A
30 < PGV	B

Table 10. Laterals – Ground Shaking

Inches	Any Lateral
0 < PGD ≤ 2	A
2 < PGD ≤ 12	B
12 < PGD	C

Table 11. Laterals – Liquefaction, Landslide and Surface Faulting

Design Categories

There are five design categories. Category A denotes standard (non-seismic) design. The following summarizes the general design approach for Categories B, C, D and E:

- B = restrained with extra valves
- C = B + better pipe materials
- D = C + quantified seismic design; or provide bypass system.
- E = D + peer review (it is strongly recommended that FEM method be used for any pipe with Classification E)

Tables 12 to 19 provide guidance for seismic pipe design using the chart method based on the categories A through E. Note. This guidance is based on commonly available pipe and joinery as of 2004. As new pipe products become available, they can be used in the chart method as long as suitable justification (FEM, test, etc.) is provided to show that the pipe meets the intended reliability of the pipe and performance of the pipe network as a whole.

Design Category	Cost Effective Design Approach	Notes
A	Standard	
B	Extended Joints	
C	Restrained Joints	
D	Extended and Restrained Joints	Standard with bypass
E	Special Joints	Standard with bypass

Table 12. Ductile Iron Pipe

Design Category	Cost Effective Design Approach	Notes
A	Standard	
B	Standard with extra insertion	
C	Restrained Joints	
D	Extended and Restrained Joints	Standard with bypass
E	Not recommended	Standard with bypass

Table 13. PVC Pipe

Design Category	Cost Effective Design Approach	Notes
A	Single Lap Weld	
B	Single Lap Weld	Weld t = pipe t
C	Double Lap Weld	Weld t = pipe t
D	Double Lap Weld / Butt Weld	D/t max 110 in PGD zones
E	Butt Weld	D/t max 95 in PGD zones

Table 14. Welded Steel Pipe

Design Category	Cost Effective Design Approach	Notes
A	Standard	
B	Extended Joints	
C	Restrained Joints	
D	Extended and Restrained Joints	Standard with bypass
E	Not recommended	Standard with bypass

Table 15. Gasketed Steel Pipe

Design Category	Cost Effective Design Approach	Notes
A	Gasketed or Single Lap weld	
B	Single Lap Weld	Weld t = pipe t
C	Double Lap Weld	Weld t = pipe t
D	Not recommended	Standard with bypass
E	Not recommended	Standard with bypass

Table 16. CCP & RCCP Pipe

Design Category	Cost Effective Design Approach	Notes
A	Standard	
B	Butt Fusion Joints	
C	Butt Fusion Joints	
D	Butt Fusion Joints	
E	Butt Fusion Joints	

Table 17. HDPE Pipe

Design Category	Cost Effective Design Approach	Notes
A	Standard	
B	Soldered joints	
C	Soldered joints	Expansion loop / Christie box / Other box

Table 18. Copper Pipe

Design Category	Cost Effective Design Approach	Notes
A	Standard	
B	Dresser-type coupling	
C	Multiple dresser couplings	
D	EBAA flextend type couplings	
E	Not recommended	Relocate hydrant

Table 19. Segmented Pipelines Used as Hydrant Laterals

Design Category	Cost Effective Design Approach	Notes
A	Bolted, Single Lap Weld, Fusion Weld	
B	Bolted, Single Lap Weld, Fusion Weld	Weld t = pipe t
C	Bolted, Double Lap Weld, Single Lap Weld with fiber wrap, Fusion Weld	Weld t = pipe t
D	Bolted, Double Lap Weld, Single Lap Weld with fiber wrap, Butt Weld, Fusion Weld	Bolted, Double Lap Weld, Single Lap Weld with fiber wrap, Fusion Weld
E	Bolted, Double Lap Weld, Single Lap Weld with fiber wrap, Butt Weld, Fusion Weld	Bolted, Double Lap Weld, Single Lap Weld with fiber wrap, Fusion Weld

Table 20. Continuous Pipelines Used as Hydrant Laterals

In addition to the design categories in Tables 12 to 20, the following additional requirements are made. These recommendations are cumulative (For C, include B and C recommendations).

- B. Add isolation valves on all pipes within 50 feet of every intersection, for example, four valves on a four-way cross.
- C. Maximum pipe length between connections for segmented pipe is 16 feet, or as otherwise justified by ESM or FEM.
- D. Maximum pipe length between connections for segmented pipe is 12 feet, or as otherwise justified by ESM or FEM.

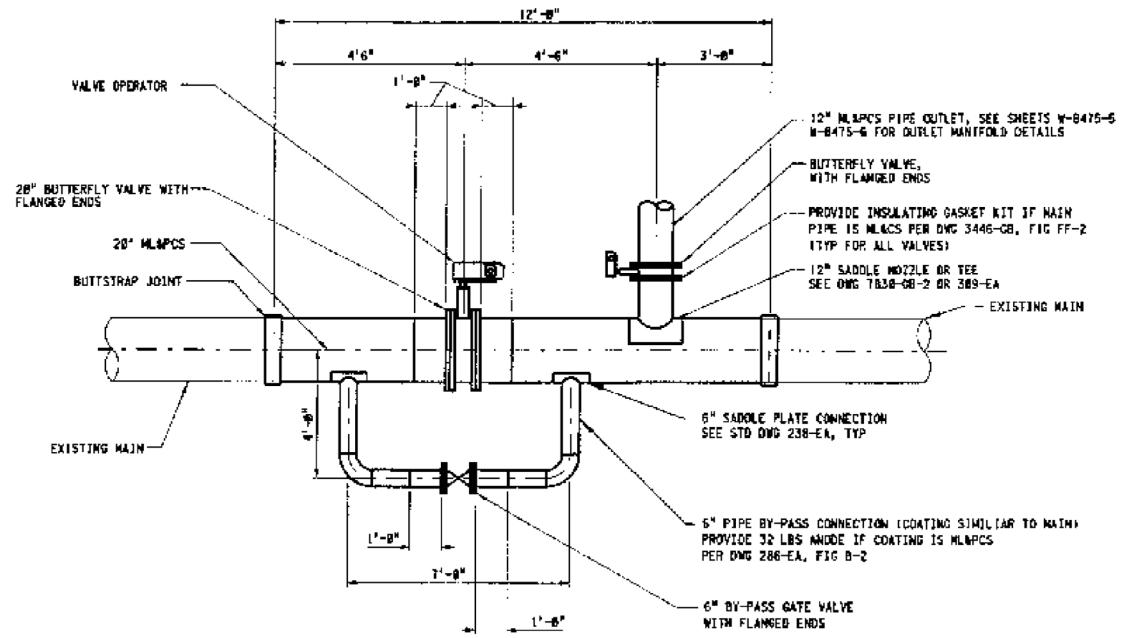
Bypass Pipelines

During design of a pipeline, it is typical to perform some preliminary seismic and hazard investigation. A geotechnical engineer can perform literature search of available publications and assess the seismic setting of the pipeline and identify potential hazards such as fault crossings, landslides, and zones of potential liquefaction.

With this information, the pipeline design engineer can often times route the pipeline to avoid well-defined hazards. This is the most cost-effective approach for minimizing seismic-related damage to a pipeline. However, sometimes there is no feasible way to avoid a hazard and the pipeline must be routed through the hazard.

Instead of using a higher Category Design (such as D or E), the owner can elect to provide a bypass capability, as long as the owner has the ability to install the bypass within about 1 day after the earthquake, and in consideration of the entire post-earthquake response. Bypass capability might be the most cost effective approach to mitigate many fault and landslide crossings for Function Class III pipelines. Bypasses can be used in retrofitting existing pipelines or for new construction where loss of service cannot be tolerated for more than one day.

A typical bypass is illustrated in Figure 2, consisting of a line isolation valve, if none previously existed, and a 12-inch diameter connection and manifold assembly on either side of the defined hazard. In order for the bypass to be used effectively, the hazard must be relatively well defined. Each of the manifolds is configured to accept one or multiple large diameter hose connections. In the event of a seismic event that results in a pipeline failure within the bounds of the hazard, the hazard isolation valves are closed, thereby stopping leakage at the point of failure. The hose is then deployed across the ground between the two manifold assemblies and serves as a temporary pipe bypass, allowing restoration of flows through the system. Figure 3 shows a deployed bypass system at a fault crossing where deployment of three flex hoses was possible.



Typical Isolation Valve with Bypass

Figure 2. Bypass Manifold Assembly

Figure 3. Flex Hose Attached to Manifold Outlets

The criteria for the bypass system components are included in Table 21. So called "large diameter flex hose" (diameter ~5-inches) will generally not provide sufficient flow rate at a reasonable pressure drop, for distances on the order of 1,000 feet between manifolds. So called "ultra large diameter flex hose" (diameter ~12-inches) can provide high flow rates at separation distances of 1,000 feet (or more). There are pros and cons with using either 5-inch or 12-inch hose, including: flow rate and pressure drop; cost; storage life; deployment effort and time; hose breakage and resultant pipe whip; etc.

Description	**Criteria**
Pipe Materials	Mortar-lined and mortar- or tape/epoxy-coated steel pipe Field joints shall be flanged, welded, or mechanically coupled with suitable restraint Design for anticipated internal, external, and transient loading conditions Provide cathodic protection as needed
Manifold Pit	Precast reinforced concrete with seismic design factors suitable for site Traffic rated steel plate cover Sized for easy hose deployment
12-inch Valves and Smaller	Butterfly or Gate
Flexible Hose	12 -inch flex hose, burst pressure ~ 400 psi, operating pressure ~150 psi. Distances up to 1,000 feet or more at flow rates of up to 5,000 gpm 5-inch fire hose from local Fire Department. Distances up to 1,000 feet at flow rates of up to 500 gpm Connections to be coordinated with manifold configuration

Table 21. Bypass System Components Criteria

CONCLUSIONS

It is the intent of these Guidelines to provide a unified, comprehensive and simple approach that can be readily adopted by water utilities for the design of new pipeline installations. The draft Guidelines are available for public comment through January 2005. They may be obtained via the Internet at: http://homepage.mac.com/eidinger/ (follow the link to downloads, and then download Seismic Guidelines.doc.) Comments should be sent to any of the authors.

The Guidelines may result in changes in pipeline installations in moderate and high seismic areas throughout the United States. Given the large economic consequences of widespread pipeline damage, the authors believe that the extra reliability afforded by these changes is worthwhile and cost effective. We hope that the Guidelines will spur water utilities to procure better pipelines in high hazard locations; in turn, the pipeline manufacturers will manufacture and supply better products. This is, in part, a "chicken and egg" process, since prior to the current moment (late 2004 – early 2005) we have not had the Guidelines for water utilities; nor have we always had suitable cost effective pipelines provided by manufacturers to meet the Guidelines.

ABBREVIATIONS AND UNITS

Customary US units (inches, pounds, gallons) are used in this paper. Conversions to SI units are provided below. All pipe sizes are in customary US units; conversion of a customary pipe size (such as 12-inch diameter) to SI units has no precision, as a 12-inch pipe may often have outside diameter anywhere from ~12-inches to ~13-inches.

ALA	American Lifelines Alliance
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
ESM	Equivalent Static Method
FEM	Finite Element Method
FEMA	Federal Emergency Management Agency
JWWA	Japan Water Works Association
MMC	Multihazard Mitigation Council
NIBS	National Institute of Building Sciences
PGA	Peak Ground Acceleration (g)
PGD	Permanent Ground Deformation (1 inch = 2.54 cm)
PGV	Peak Ground Velocity (1 inch/sec = 2.54 cm/sec)

inch	inch (1 inch = 2.54 cm)
feet	feet (1 foot = 12 inches = 30.48 cm)
g	gravity constant (1g = 386.4 inch/sec^2 = 981 cm/sec^2)
gpm	gallons per minute (1 gpm = 3.785 liters per minute)
psi	pounds per square inch (1 psi = 6.895 kilopascals)
sec	second