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Evaluation of Seismic Vulnerability and Failure Modes for Pipelines

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Abstract

One of the most appropriate methods to assess seismic vulnerability, is reviewing damages occurred during past earthquakes, especially for industrial plants, such as oil and petrochemical facilities. In recent 50 years, mega quakes have happened in regions with important oil facilities, so a detailed investigation of damages can lead to a better estimate of probable losses in future events. Also, examination of structures and equipment function during earthquakes can reveal defects in design, construction and maintenance.

In this paper, after brief review of previous important earthquakes and consequent damages, reasons for specific concern about pipelines are being presented. Then, a table describing prioritization of activities related to the risk mitigation is shown and defining pipeline vulnerabilities, a very important part of the paper; is placed afterwards. Failure modes of above and underground pipelines are explained later.

Keywords: earthquake; pipeline; vulnerability; rehabilitation; failure.

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1. INTRODUCTION

Due to continuous changes in seismic codes caused by increasing human knowledge and experience about earthquakes, seismic rehabilitation of existing structures and components is inevitable. First step in rehabilitation would be vulnerability assessment and one of the most helpful means for a suitable assessment is utilizing lessons learned from previous earthquakes. This would be reasonable because real situation of proposed structure with real ground motion and engineering judgment, are combined to gain a result for future use. Also, this is a confirmed method for collection of new codes and guidelines.

In this paper, pipelines are specifically investigated and reasons for seismic vulnerability assessment related to different economical, ecological and industrial aspects are explained. Then, some factors causing vulnerability and examples of real damages to pipelines caused by earthquakes are stated, and finally probable failure modes of pipelines are expressed.

2. Reasons for seismic assesment and rehabilitation of pipelines

Earthquake, is a natural disaster causing many financial and industrial losses and fatalities every now and then in the world. Besides human losses in cities and villages, it can cause huge economical and environmental losses through damages in industrial regions. On August 1999, earthquake in industrial zone of Izmit, Turkey, inflicted about 17 billion $ loss, mostly because of industrial damages and its direct and indirect effects. One important reason for huge detriment in Toprus Refinery was continuation of liquid flow through pipelines by reason of defect in valves installed on pipelines. Also, fire started after a concrete flare fell over pipelines and broke them and situations get worse when damage in water pipelines and pump stations prevented transferring water from adjacent lake for 4 weeks. In San Salvador 2001 earthquake, main pipelines maintaining city water through connection to water reservoirs, experienced 21 million $ loss, such as San Francisco 1906 earthquake in which pipelines broke at intersections with faults and where soil was soft. Anyway, Coalinga 1983 and Norway 1987 events have shown that well-designed pipelines behave suitable during earthquakes.

One Important difference between oil and gas pipeline, and water pipeline is that the latter is usually network shaped, while the former is linear, so damage in any part of oil and gas pipeline can completely stop the flow of material and function of dependent processes. In other words, repair cost of damaged pipeline would be a small portion (about 10%) of total damage cost. Table 1 portrays some probable after-effects caused by oil and gas pipeline damages and prioritization to adjust them.

3. DEFINING SEISMIC VULNERABILITY CAUSES FOR PIPELINES

To reduce seismic vulnerability, having common definitions for vulnerability causes is essential. Followings are some major causes of seismic vulnerability for pipelines.

3.1. Wave propagation

Period and amplitude of waves propagated through earthquake are influenced by amount of energy released, distance to seismic source, type of wave, soil type in wave distribution area and region topography. During wave propagation, energy is transmitted to above and underground structures, such as pipelines. It is probable that underground pipelines experience transmitting displacements during wave propagation.

3.2. Permanent ground displacements

Seismic waves can permanently cause displacements in site and restraints. These displacements are some of most important reasons to above and underground pipeline failures during earthquakes and can be classified as faulting, liquefaction, landslide and uplift.

Table 1: Impacts of earthquake-generated crude oil pipeline failure (Tierney 1992)

Impacts	*Phase of Emergency*		
	Emergency Response	*Short-Term Recovery*	*Long-Term Recovery*
1- *Oil Spill Effects*			
Loss of Oil	*X*	*X*	
Surface Water Pollution	*X*	*X*	
Ground Water Pollution	*X*	*X*	*X*
Threats to Human Health	*X*	*X*	
Threats to Wildlife	*X*	*X*	*X*
Threats to Vegetation	*X*	*X*	*X*
Fire hazards	*X*		
Threats to Water Supply	*X*		
Damage to Water Treatment Facilities	*X*	*X*	
Disruption of Crude Oil Supply	*X*	*X*	
Threats to Economic Activity	*X*	*X*	*X*
Threats to Aesthetic Value	*X*	*X*	*X*
2- *Response-Related Damages*			
Oil Containment and Cleanup	*X*		
Oil Waste Disposal	*X*	*X*	*X*
Repair of Pipeline and Other Components	*X*		
Restoration of Pipeline and Other Components	*X*	*X*	
Containment of Secondary Hazards	*X*		
Protection of Health, Welfare and Residents	*X*	*X*	*X*
Protection of Wildlife	*X*	*X*	*X*
Protection of Vegetation	*X*	*X*	*X*
Enhanced Pipeline Maintenance		*X*	*X*
Restoration of Crude Oil Supply	*X*	*X*	
Alternative Water Supply Acquisition	*X*	*X*	

3.2.1. Faulting

Usually, faulting can be observed at ground surface. Since pipelines are very sensitive to displacement (and also velocity) rather than acceleration, faulting can cause drastic destruction to them. Faulting can be vertical, horizontal or a combination of both directions.

3.2.2. Liquefaction

Liquefaction happens when soil changes from a solid state to a liquid state because by high frequency motions of earthquake, effective strengthening stress of soil becomes negligible or zero, and subsequently, soil cannot bear any shear stress, just like liquids do. Liquefaction is expected to happen in soils without cohesion, and where the underground water surface is reasonably high. This phenomenon can make underground equipment come up, and aboveground equipment sink. Probability of happening and severity of liquefaction increases by increase in earthquake duration.

3.2.3. Landslide

Even without liquefaction, ground motion can move huge amounts of soil in hills, where this movement is related to soil slope, strength, moisture, and consolidation ratio. Probability of landslide refers to duration and magnitude of earthquake. Landslide can block access ways and cause notable damage to both above and underground pipelines.

3.2.4. Uplift

Uplift is usually caused by vertical component of ground motion and has most destructive effects on inlets and outlets (attachments and flanges.)

4. Pipeline damages in previous earthquakes

Although there is a good databank of earthquake damages in residential regions, lack of information is evident in industrial areas. This data shortage becomes more crucial about pipelines. Some reasons for date inefficiency in industrial areas are:

- They have been built in recent decays, and are newer than residential regions.
- They are complex and smaller than residential areas, so probability of damage decreases due to their size.
- Even if an earthquake has effects on industrial plants, equipment has been more investigated than pipelines.
- Pipelines far from urban areas have not been considered carefully because of distance and access problems.

Anyway, in spite of data limitations, some records from damages to pipelines after earthquakes have been investigated and relevant results are illustrated briefly.

4.1. 1971 San Fernando (6.6)

Also known as Sylmar earthquake, caused about 80 reported destruction in welded underground pipelines, the worst of which noticed in oxy- acetylene welds made in 1930. Although pipeline was located in an uplift-susceptible area but damage occurred because of pressure forces wrinkling the pipe. Newer pipes showed less damage in the same area.

4.2. 1989 Loma Prieta (6.9)

The East Bay Municipal Utilities District identified over 120 water pipeline breaks following the earthquake. Some of the significant damage included a break in a 60-inch raw water pipeline supplying the Sobrante filter plant and several breaks in a 20-inch cast iron pipeline near Laney College in downtown Oakland.

The San Jose Water Company reported 155 pipe breaks, 67 of which were repaired within the first 48 hours, mostly appeared to be related to bell couplings at adjacent pipe segments.

For gas pipelines, most of the serious damage reported by Pacific Gas & Electric Company (PG&E) occurred to gas mains and service lines. In wastewater system, Damage to two large-diameter (96-inch and 84-inch) outfall lines has resulted in costly repairs which will be necessary for San Francisco's clean water system. (Dames and Moore's Earthquake Engineering Group 2005)

4.3. 1994 Northridge (6.7)

This event caused about 1400 water, gas and fuel pipeline breaks in the San Fernando Valley area. Many of the breaks occurred in mapped areas of high liquefaction potential. Outside the zone of high liquefaction potential, the dispersed pattern of breaks is attributed to old brittle pipes damaged by ground movement. In the Granada Hills area pipe breaks from water mains resulted in soil erosion and formation of large craters. On Balboa Boulevard a 22- inch pipe suffered two breaks, one in tensile failure and the other in compressive failure. These pipe failures were located in a ground rupture zone perpendicular to the pipeline. Some broken water and gas lines were found to have experienced 6 to 12 inches of separation in extension. A 85 inch sewage pipe ruptured in the Jensen Filtration Plant. (Ferrito 1997)

4.4. 1999 Izmit (7.4)

This earthquake is considered as one of the most important events in industrial plants. Tupras refinery experienced severe damage due to fire because pipeline transferring water from neighbor lake were impaired and could not function properly, so the refinery was dependent on internal water reservoirs, which were insufficient (figure 1). Along with this pipeline, some internal piping such as aboveground polyester pipes and concrete ducts had marginal damages.

4.5. 2001 San Salvador (7.6-6.6)

Two earthquakes happened in January and February 2001. While pipelines in urban areas showed good behavior, rural areas experienced serious damage, mostly caused by huge landslides.

4.6. 2002 Alaska (7.9)

What makes this event valuable to consider, is crossing the long and important Alaska crude oil transmission pipeline called "TAPS" with 1287 km length and 48 inch diameter through the faulting zone. About half length of this pipeline is above ground. In figure 2 the pipeline route, important faults and events happened near the pipeline are portrayed. The 2002 earthquake has been caused by "Denali" fault, crossing the pipeline obviously. Appropriate and conservative design of the pipeline and also applying sufficient ductility in supports led to minor damage to this pipeline so that oil transmission did not stop at all. In figure 3, an aboveground part of pipeline and its supports are shown.

Figure 1: Damaged water pipeline in Tupras refinery

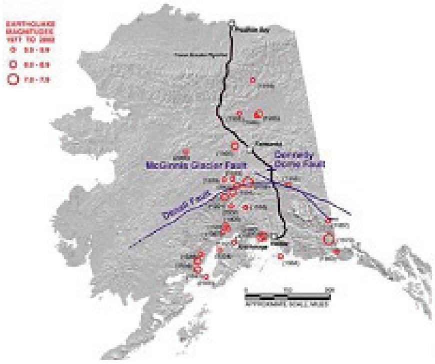

Figure 2: TAPS pipeline and crossing faults

Figure 3: TAPS pipeline and supports

(Hall WJ et al. 2003)

5. Failure modes of pipelines

5.1. Stiffness Distribution

A major part of damages to pipelines is due to inappropriate stiffness distribution. If a very stiff pipe (with large diameter, for example) which is not laterally supported is connected to a pipe with smaller diameter, in lateral displacements, damage in attachment area is expected. Also if large diameter pipes are directed inside the earth in a low length, such as in tanks, damage could be expected (figures 4 to 6).

5.2. Attachments

Attachment such as regular flanges can be vulnerable specially exposed to high PGD and PGV. A solution is using flexible couplings (figure 7).

5.3. Proximity and Impact

Adjacent and condensed pipelines in plants and their interaction in earthquake might cause damages, if no proper solution, such as suitable isolation between pipelines is devised (figure 8).

5.4. Inappropriate Supports

This problem mostly occurs in case of weak maintenance system and can cause serious problems in industrial plants during earthquakes (figure 9).

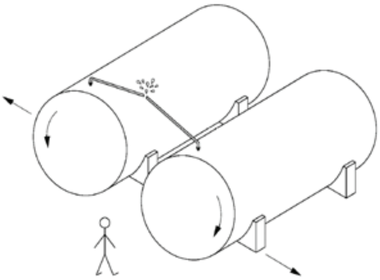

Figure 4: Unanchored Tanks Slide and Twist

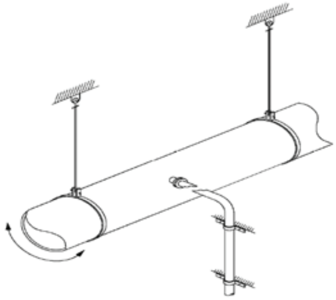

Figure 5: Suspended Header and Stiff Branch (ALA 2002)

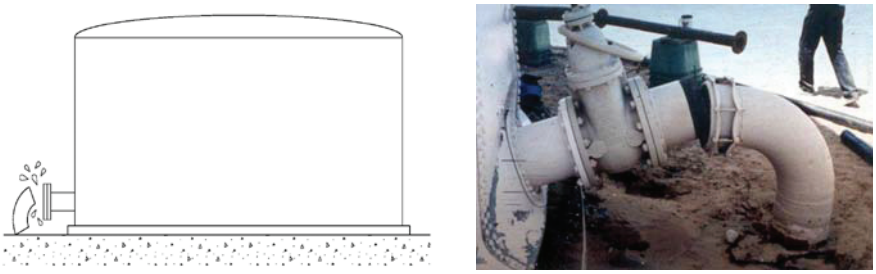

Figure 6: Unanchored Flat Bottom tank Slides and Rocks (ALA 2002)

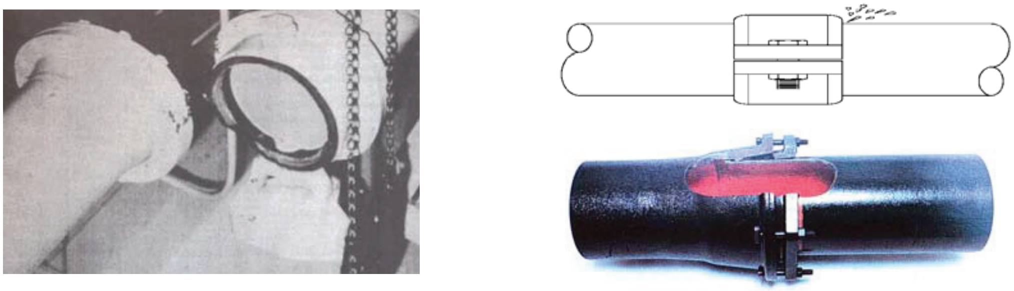

Figure 7: Grooved Coupling Leak from Excessive Bending and a Type of Flexible Coupling (Flores R et al. 2002)

Figure 8: Adjacent Pipelines are vulnerable due to interaction effects

Figure 9: Inappropriate Supports

6. CONCLUSIONS

Results of different post-earthquake assessments have shown that flexibility is a key point in pipeline safety in earthquakes. Since pipelines are sensitive to velocity and displacement rather than acceleration, utilizing flexible joints and supports, in addition to considering proper seismic inputs and design methods, can lead to build a safe pipeline, even in highly seismically active regions. Pipelines, due to their intrinsic function, are inevitable to pass through faulting zones and faults in most cases, but it is not impossible to design and build a safe pipeline.

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