Seismic Design of Buried Pipelines in Indian Context

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ABSTRACT

Pipelines are important lifeline facilities spread over large area and encounter a range of seismic hazards and soil conditions. Many buried pipelines in India run through high seismic areas and therefore are exposed to considerable risk. This paper describes the various modes of pipeline failures. It reviews pipeline performance in past Indian earthquakes. Though the world scenario on seismic design of pipelines has advanced a lot, still in India there is no uniform guideline available for seismic design of pipelines. For the growing network of pipelines in India, it is becoming very important to establish a standard for seismic design of pipelines to ensure a uniform approach to the problem, and ensure a minimal degree of safety.

INTRODUCTION

Pipelines are generally spread over a large geographical region and encounter a wide variety of seismic hazards and soil conditions. The pipelines are generally buried below ground for aesthetic, safety, economic and environmental reasons. The gas and liquid fuel pipelines are generally welded at the joints to act as a continuous pipeline. On the other hand, the water supply pipelines with mechanical joints are generally treated as segmented pipelines.

Modern pipelines manufactured with ductile steel with full penetration butt welds at joints possess good ductility. It has been observed that the overall performance record of oil and gas pipeline systems in past earthquakes was relatively good. However catastrophic failures did occur in many cases, particularly in areas of unstable soils. Failures have mostly been caused by large permanent soil displacements (*FEMA-233*).

FAILURE MODES OF PIPELINE

From the past observations, about 3% of natural gas pipeline failures in USA are due to the effect of ground movement due to seismic event (Figure-1). The main seismic hazards that are responsible for pipeline failure can be described as:

1) Seismic wave propagation
2) Abrupt permanent ground displacement (faulting)
3) Permanent ground deformation (PGD) related to soil failures:

a. Longitudinal PGD
b. Transverse PGD
c. Landslide

4) Buoyancy due to liquefaction

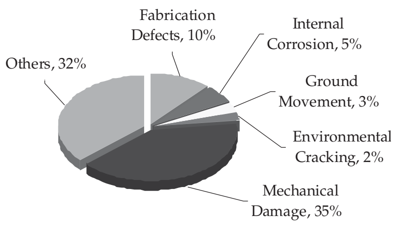

Figure 1: Causes of natural gas pipeline failures in USA during 1884-1990 (PRCI, 2003).

The main failure modes of both continuous and segmented pipelines are summarized in the following.

Continuous pipeline

Tensile failure

Tensile strain in the pipeline can arise due to any of the seismic hazards (e.g., faulting, landslide, liquefaction, and relative ground motion) at pipe supports. Figure-2 illustrates the effect of landslide on the pipeline resisting high tensile strain.

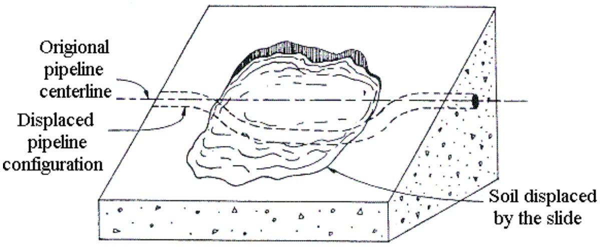

Figure 2: Effect of landslide on pipeline resisting tensile strain (ASCE, 1984*)*.

Local buckling

Local buckling or wrinkling in pipeline occurs due to local instability of the pipe wall. Once the initiation of local shell wrinkling occurs, all subsequent wave propagation and geometric distortion caused by ground deformation tend to concentrate at these wrinkles. Thus, the local curvature in pipe wall becomes large and leads to circumferential cracking of the pipe wall and leakage. This is a common failure mode for steel pipes. Figure-3 illustrates local buckling of a 77 inch welded steel pipe during the 1994 Northridge earthquake.

Figure 3: Locally buckled steel gas pipeline in the compression zone at North slope of Terminal Hill in 1994 Northridge earthquake. (EERI, 1995)

Beam buckling

Beam buckling of a pipeline is similar to Euler buckling of a slender column; the pipe undergoes an upward displacement. The relative movement is distributed over a large distance and hence the compressive strains in the pipeline are not too large and the potential for tearing of the pipe wall is less. For this reason, beam buckling of a pipeline for a ground compression zone is considered more desirable than local buckling. Beam buckling generally occurs in pipelines buried at shallow depths of about 3 feet or less. This can also happen during post-earthquake excavations, which are carried out deliberately to relieve compressive strain in the pipes. Figure-4 shows beam buckling of a water pipeline made of iron during the M7.8 San Francisco earthquake in 1906.

Figure 4: Beam buckling of a water pipeline made of iron. (USGS Photo Library)

Segmented pipeline

Axial pull-out

In the areas of tensile ground strain the common failure mechanism of a segmented pipeline is axial pull-out at joints, since the shear strength of joint caulking material is much less than that of the pipe. Figure-5 shows a 30cm diameter cast iron pipeline pulled apart 25cm during 1976 Tangshan earthquake.

Figure-5: Axial pull-out at the joint of a water supply pipeline at Tangshan East Water Works in Tangshan Earthquake 1976 (EERL, 2004)

Crushing of bell-and-spigot joints

In areas of compressive strain, crushing of bell-and-spigot joints is a very common failure mechanism. Figure-6 shows the failure of a cast iron pipe due to failure of bell and spigot joint at Navlakhi port area during Bhuj earthquake of January-26, 2001.

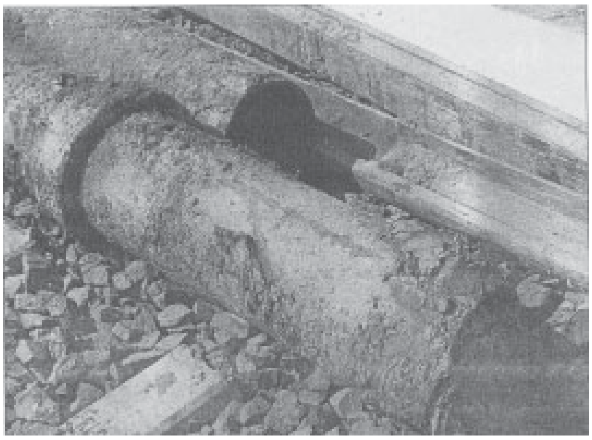

Figure-6: Failed cast iron pipe due to failure of bell and spigot joint at Navlakhi port due to lateral spread in 2001 Bhuj earthquake (ASCE, 2001)

Flanged joint failure

In the areas of tensile ground strain, flanged joint pipeline may fail at joint due to breaking of the flange connection. Figure-7 shows a flanged joint pipe failure due to higher tensile strain.

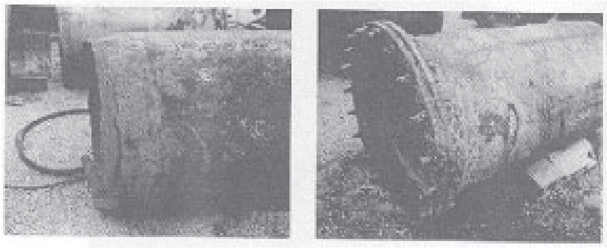

Figure- 7: Flanged joint pipe failure. (ASCE, 1997)

Circumferential flexural failure and joint rotation

When a segmented pipeline is subjected to bending induced by lateral permanent ground movement or seismic shaking, the ground curvature is accommodated by some combination of rotation of joints and flexure in the pipe segments. The relative contribution of these two mechanisms depends on the joint rotation and pipe segment flexural stiffness. Figure-8 shows the pipeline leaking at its joint due to excessive bending in 2004 Sumatra earthquake.

Figure-8: Leaking at bell and spigot joint of water supply pipeline due to bending at Shippy Ghat, Port Blair in M9.0 Sumatra earthquake of 2004 (Photo: Suresh R Dash)

SEISMIC RISK TO PIPELINES IN INDIA

Pipelines play a key role in the gas and oil supply services in India. Figure-9 and 10 show major oil and gas pipeline networks of India. The Gas Authority of India Limited (GAIL) operates and maintains over 1800 km of regional pipelines in western, southern and eastern regions of India and is planning to establish a National Gas Grid by laying approximately 7000 km of high-pressure transmission gas pipelines in 15 states across the country. (http://www.gailonline.com/newsevents/).

Indian Oil Corporation Limited (IOCL) supplies petroleum products to the various major demand centers and feeds crude oil to four major inland refineries with a vast network of pipelines throughout India. IOCL pipelines comprise of 4762 km of product pipeline and 2813 km of crude oil pipeline. (http://www.iocl.com/business_pipeline.asp). Many short oil and gas pipelines are also running throughout India whose data are not included herein.

The network of water supply and sewage pipelines are much bigger than the gas and oil pipeline grid. But data on these is not readily available. The seismic risk involved in water pipelines is lower than that in oil and gas pipeline systems. Therefore, from the view point of seismic design, greater importance is usually given to oil and gas pipelines as compared to water or sewage pipelines.

Most of the pipelines used for supplying oil and gas are buried underground. From the seismic zone map of India (Figure-11), it is seen that many of the pipelines are running through the high seismic regions.

Table-1 provides some information, even though incomplete, on the performance of pipelines in some past Indian earthquakes. Table-1 should be viewed with two constraints: (a) pipeline network has been developed in recent years only and no damage reports in the earlier earthquakes are expected, and (b) there is no systematic data collection after most earthquakes on failure of pipelines. Considering the seismicity of India and the risk that the pipeline networks are exposed to, it is important that adequate consideration be given to seismic design of pipelines.

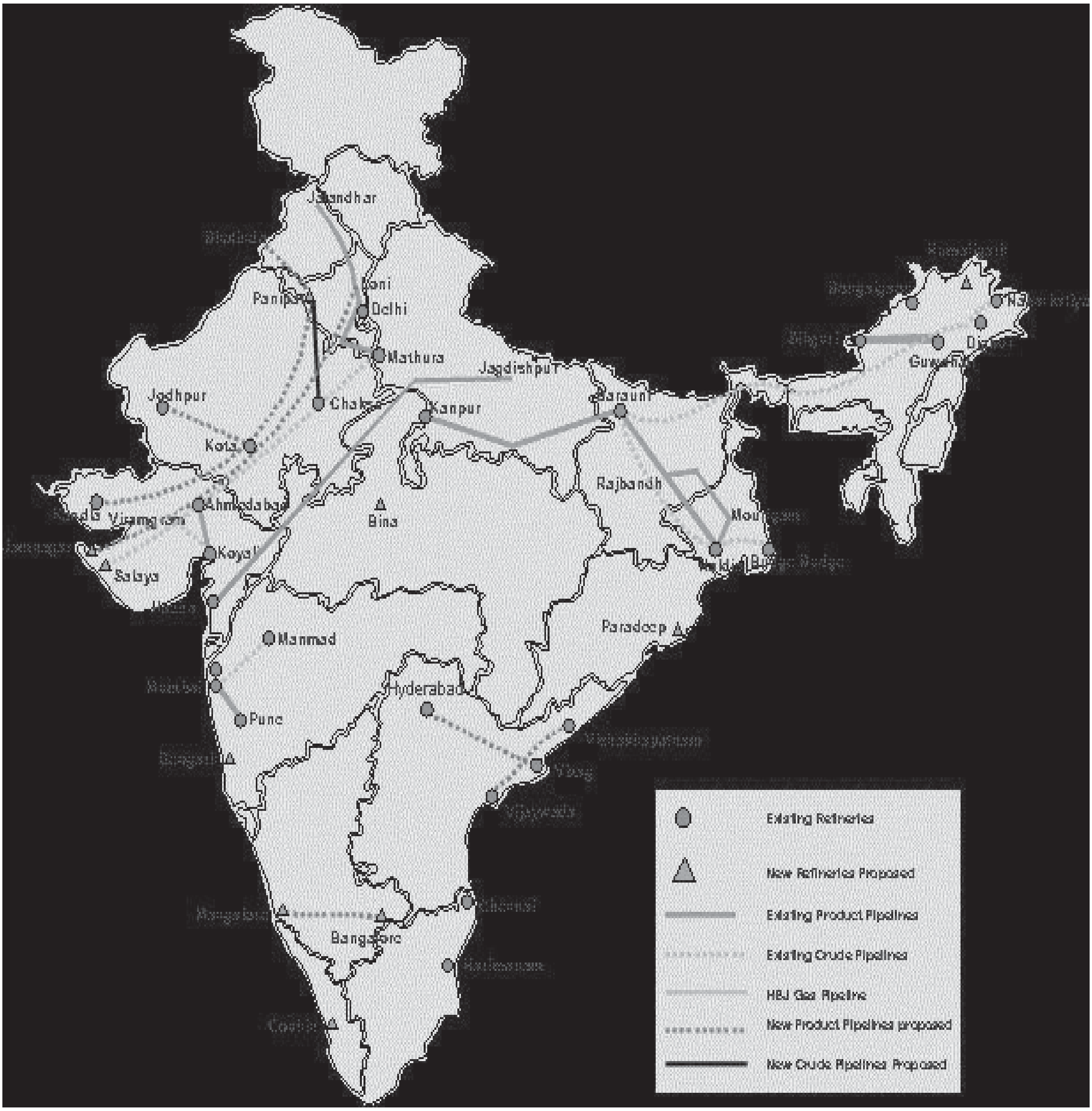

Figure-9: Major oil and gas pipeline network of India (www.iocl.com)

Figure-10: National gas grid of India (www.gailonline.com)

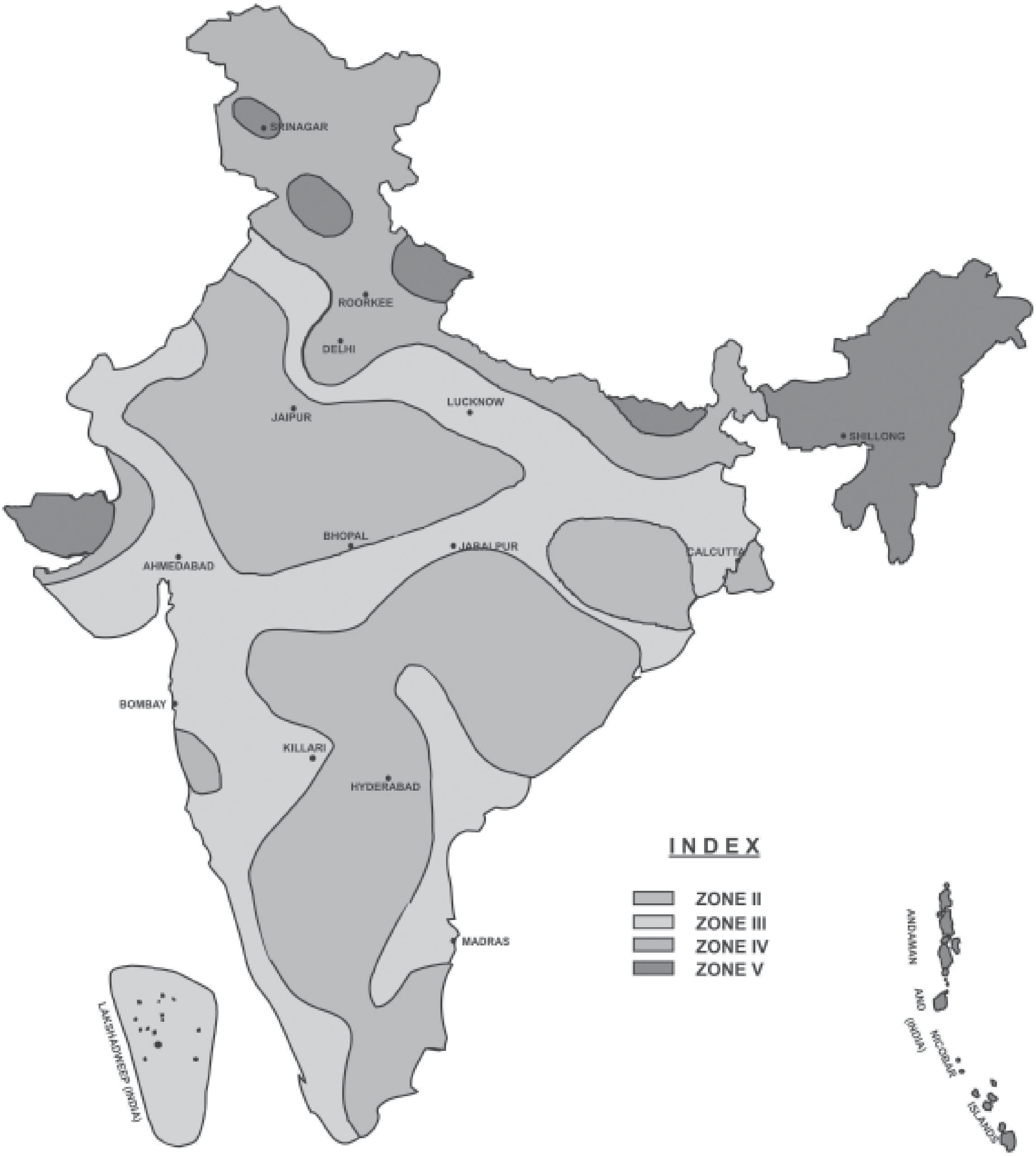

Figure-11: Seismic zone map of India

Table-1: Performance of pipelines in some past earthquakes in India

Description of earthquake	M	Pipeline performance
Sumatra Earthquake, Dec-26, 2004	9.0	Most of the water pipelines were damaged severely in Andaman and Nicobar Islands area. The oil pipelines performed better. There were some cases of breakages at junctions of pipes with the facilities like tanks, machines, etc.
Gujarat Earthquake, January-26, 2001	7.7	Most of the liquid fuel facilities not affected. Some damage occurred at the junctions of pipeline to the equipments at pump stations.
Chamoli Earthquake, March-29 1999	6.8	Water supply to Chamoli and Gopeshwar towns was disrupted due to damage to the pipelines by the landslides.
Bihar Earthquake, August -21, 1988	6.6	Some minor damage to few facilities of IOCL refinery at Barauni (Hulyalker, 1988).

DEVELOPMENT OF SEISMIC DESIGN GUIDELINES

The petroleum industry in the United States developed interest in seismic design after the 1933 Long Beach earthquake. A major push to research on the subject was given after the massive damage of pipeline systems due to 1971 San-Fernando earthquake. In 1974 the American Society of Civil Engineers (ASCE) formed a Technical Council of Lifeline Earthquake Engineering (TCLEE) to formally carryout continual development of guidelines for seismic design of lifeline systems.

In a 1977 conference of ASCE, Kennedy et al. (1977) and Hall and Newmark (1977) proposed seismic design criteria for pipelines and facilities. In 1984, ASCE first published formal guidelines (ASCE, 1984) for seismic design of pipeline systems to provide guidance on design, operation and maintenance of pipelines.

In 1974, the first seismic design code “Technical Standard for Oil Pipelines (JRA, 1974)” was developed by Japan Roads Association (Masayuki et al., 1992). In 1979, seismic design criteria for waterworks and in 1982, seismic design criteria for high, medium and low pressure pipelines were developed in Japan (Masayuki et al., 1992).

In India, there is no specific standard or guideline that deals with seismic evaluation and design of pipeline systems. Most of the agencies are following different codal provisions and guidelines of other countries. Some have developed their in-house procedures for seismic analysis and design. Hence, there is no uniform approach to seismic protection of pipelines in India. Considering this need, the Gujarat State Disaster Management Authority (GSDMA) have sponsored a project at IIT Kanpur for development of such guidelines. The first draft of the same will be available shortly.

METHODOLOGY FOR ANALYSIS AND DESIGN

The philosophy of seismic design for the pipelines is to design the pipeline such that it will be able to maintain its supplying capability even after considerable local damage due to high intensity earthquakes. The pipelines must be designed to have sufficient stiffness, strength, and ductility to resist the effects of seismic ground motions. The most difficult part in pipeline design is to assess the seismic hazard associated with it. Sophisticated analysis cannot give better results if the seismic input to the analysis is off the mark.

For the seismic design of pipelines, the main considerations are seismic wave propagation and ground displacements due to soil failure. Mostly the strain in the pipeline is the governing criteria for designing the pipeline. Therefore, the procedure that is mainly employed for the pipeline design is displacement based. For the analysis, the nonlinearity of the pipe and the soil should be modeled. For approximate analysis pseudo static method can be employed, but for detailed analysis nonlinear time history analysis or response spectrum analysis must be carried out.

CONCLUSIONS

Pipelines are generally buried and spread over a large geographical area. Tensile rupture, local or beam buckling are the principal modes of failure for continuous pipeline, whereas the rupture of individual pipelines, pull out of joints, excessive bending at joints are the principal failure modes of segmented pipeline. We have pipeline grid spread all over India, and many of the pipelines run through high seismic zones. In world scenario, the development of guidelines and codal provisions started from 1970’s. However India is only now starting to develop its own standard for seismic design of pipelines.

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