Research Objectives

The objectives of the research are to: 1) simulate in the laboratory full-scale permanent ground deformation (PGD) effects on steel pipelines with elbows, 2) develop an extensive and detailed experimental database on pipeline and soil reactions triggered by earthquake-induced PGD, and 3) refine and validate analytical models so that complex soil-pipeline interactions can be numerically simulated with the precision and reliability necessary for planning and design. To accomplish these objectives, an international partnership was organized, involving the Tokyo Gas Company, Ltd., MCEER, and NSF through its program for US/Japan Cooperative Research in Urban Earthquake Disaster Mitigation. The project combines experimental and analytical research performed at Tokyo Gas facilities with experimental and analytical work undertaken at Cornell University. The experiments at Cornell represent the largest simulations of PGD effects on pipelines ever performed in the laboratory.

During earthquakes, permanent ground deformation (PGD) can damage buried pipelines. Earthquake-induced PGD can occur as surface fault deformation, liquefaction-induced soil movements, and landslides. There is substantial evidence from previous earthquakes, such as the 1983 Nihonkai-chubu (Hamada and O’Rourke, 1992), the 1994 Northridge (O’Rourke and Palmer, 1996), and the 1995 Hyogoken-Nanbu (Oka, 1996) earthquakes, of gas and water supply pipeline damage caused by earthquake-induced PGD. More recent earthquakes, including the 1999 Kocaeli and Duzce earthquakes in Turkey, and the 1999 Chi-chi earthquake in Taiwan, have provided additional evidence of the importance of liquefaction, fault rupture, and landslides through their effects on a variety of highway, electrical, gas, and water supply lifelines.

Gas and other types of pipelines must often be constructed to change direction rapidly. In such cases, the pipeline is installed with an elbow that can be fabricated for a change in direction from 90 to a few degrees. Because elbows are locations where flexural and axial pipeline
deformations are restrained, concentrated strains can easily accumulate at elbows in response to PGD.

The response of a pipeline elbow, deformed by adjacent ground rupture and subject to the constraining effects of surrounding soil, is a complex interaction problem. A comprehensive and reliable solution to this problem requires laboratory experiments on elbows to characterize their three-dimensional response to axial and flexural loading, an analytical model that embodies soil-structure interaction combined with three-dimensional elbow response, and full-scale experimental calibration and validation of the analytical model.

To resolve this problem, an international team was organized. The principal participants are Tokyo Gas Company, Cornell and Waseda Universities. The research also involves the University of Cambridge, UK, Rensselaer Polytechnic Institute, and the University of Southern California. Waseda University leads a consortium of Japanese university participants that include Kyoto and Yamaguchi Universities and the University of Tokyo. The work was performed as part of MCEER Program 1 on the Seismic Retrofit and Rehabilitation of Lifelines and the NSF program for U.S./Japan Cooperative Research in Urban Earthquake Disaster Mitigation.

MCEER has a long history of productive collaboration with the Japanese earthquake engineering research community. Seven U.S./Japan workshops on the earthquake performance of lifeline facilities and countermeasures against liquefaction have been co-sponsored by MCEER, and the proceedings of these workshops have been published and distributed by MCEER. The latest in this series of workshops (O’Rourke, et al., 1999) was held in Seattle, WA in conjunction with the 5th U.S. Conference on Lifeline Earthquake Engineering. The next workshop is planned during the forthcoming year in Tokyo, Japan. U.S. participants in the workshops include MAE, MCEER, and PEER researchers.

Experimental and Analytical Models

One of the deformation conditions of interest is illustrated in Figure 1a that shows a pipeline

The users of this research include: public and private utility companies, including gas distribution companies, such as Tokyo Gas and Memphis Gas, Light and Water; and water distribution companies, such as the Los Angeles Department of Water and Power (LADWP), and the East Bay Municipal Utility District (EBMUD). The research is also of interest to engineering design and consulting companies. The experimental data and analytical modeling procedures developed for this project are of direct relevance for underground gas, water, petroleum and electrical conduits.
with an elbow subjected to PGD consistent with lateral spread and/or landslides. Although lateral spreads and landslides involve complex patterns of soil movement, the most severe deformation associated with these phenomena occurs at the elbows and near the margins between the displaced soil mass and adjacent, more stable ground. The deformation along this boundary can be simplified as abrupt, planar soil displacement. Pipelines that can be sited and designed for abrupt lateral displacement will be able to accommodate complex patterns of deformation that frequently involve a more gradual distribution of movement across the pipeline. Abrupt soil displacement also represents the principal mode of deformation at fault crossings.

Figure 1b illustrates the concept of the large-scale experiments. A steel pipeline with an elbow is installed under the actual soil, using fabrication and compaction procedures encountered in practice, and then subjected to abrupt lateral soil displacement. The scale of the experimental facility is chosen so that large soil movements are generated, inducing soil-pipeline interaction unaffected by the boundaries of the test facility in which the pipeline is buried. The ground deformation simulated by the experiment represents deformation conditions associated with lateral spread, landslides, and fault crossings, and therefore applies to many different geotechnical scenarios. In addition, the experimental data and analytical modeling products are of direct relevance for underground gas, water, petroleum, and electrical conduits.

A modeling technique, named HYBRID MODEL, was developed for simulating large-scale pipeline and elbow response to PGD (Yoshizaki et al., 1999 and 2001). The model uses shell elements for the elbow where large, localized strains occur. Shell elements are located over a distance of 20 times the pipe diameter from the center point of the elbow. The shell elements are linked to beam elements that extend beyond this

![Figure 1b. Experimental Concept](image-url)

**Figure 1b. Experimental Concept** for PGD Effects on Buried Pipelines with Elbows

**Links to Current Research**

Program 1: Seismic Evaluation and Retrofit of Lifeline Networks

Program 2: Seismic Retrofit of Hospitals, Task 2.7a, Cost Benefit Studies of Rehabilitation Using Advanced Technologies

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distance. Soil-pipeline interaction under PGD is characterized by p-y and t-z curves, linking soil stresses on the pipe to the relative displacement between them. Lateral soil-pipeline interaction is characterized on the basis of laboratory experiments originally performed at Cornell (Trautmann and O’Rourke, 1985) and duplicated at Tokyo Gas experimental facilities.

In-plane bending experiments were conducted by Tokyo Gas (Yoshizaki et al., 1999 and 2001) on full-scale specimens of steel elbows in both the closing and opening modes. No leakage was observed in the closing mode, even when the opposing ends of the elbow were deformed into contact with each other and strains as high as 70% were measured. In contrast, leakage was observed in the opening mode for all cases except those in which the deformation was restricted because of the experimental loading device. The HYBRID MODEL was used to simulate the deformation behavior of the elbows using linear shell elements. Very good agreement was achieved between the analytical and experimental results for all levels of plastic deformation.

Large Scale Experiments

Figure 2 shows a plan view of the experimental setup that consisted of five main components, including a test compartment (A and C in the figure), pulley loading system (F), sand storage bin (G), sand container hoisted from storage bin to test compartment (not shown), and data acquisition system (H). The test compartment was composed of a movable box (A) and fixed box (C) within which the instrumented pipeline was installed and backfilled. The L-shaped movable box had inside dimensions of 4.2 m by 6 m by 1.5 m deep. It was constructed on a base of steel I-beams positioned over Teflon sheets that were fixed to the floor. The Teflon sheets provided a low-friction surface on which the movable box was displaced by a pulley loading system. The fixed box, which was anchored to the floor, was designed to simulate stable ground adja-
cent to a zone of PGD similar to that illustrated in Figure 1.

A 100-mm-diameter pipeline with 4.1-mm wall thickness was used in the tests. It was composed of two straight pipes welded to a 90-degree elbow (E). The short section of straight pipe (D) was 5.4 m long, whereas the longest section was 9.3 m. Both ends of the pipeline were bolted to reaction walls. The elbows were composed of STPT 370 steel (Japanese Industrial Standard, JIS-G3456) with a specified minimum yield stress of 215 MPa and a minimum ultimate tensile strength of 370 MPa. The straight pipe was composed of SGP steel (JIS-G3452) with a minimum ultimate tensile strength of 294 MPa. About 150 strain gauges were installed on the pipe to measure strain during the tests. Extensometers, load cells, and soil pressure meters were also deployed throughout the test setup.

The pipeline was installed at a 0.9-m depth to top of pipe in each of four experiments. In each experiment, soil was placed at a different water content and in situ density. All experiments were conducted to induce opening-mode deformation of the elbow.

The experimental facility was designed with the assistance of the HYBRID MODEL that was used to simulate various testing configurations and compartment dimensions. Significant characteristics of the experimental facility are its size and volume. The storage bin for the sand was over three stories tall, with a capacity for 75 tons. Approximately 60 tons of sand were moved from the storage bin into the test compartment for each experiment with a container that was hoisted with the overhead conveyor. The sand was placed and compacted in 150-mm lifts with strict controls on water content and in situ density. One of the most significant challenges during the testing was the movement and controlled placement of such large volumes of sand with water content that was intentionally changed for each experiment.

The movable box was pulled by an overhead crane with an 8 to 1 mechanical advantage obtained through the pulley system shown in the figure. The maximum capacity of the loading system was

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**Figure 3. Overhead View of Test Compartment Before (top) and After (bottom) an Experiment**
1 m of lateral displacement and 784 kN. The rate of displacement of the movable box was approximately 16 mm/s.

Figure 3 shows the ground surface of the test compartment before and after an experiment. Surficial cracks can be seen in the area near the pipeline elbow and the abrupt displacement plane between the movable and fixed boxes after the test. In all cases, planes of soil slip and cracking reached the ground surface, but did not intersect the walls of the test compartment to any appreciable degree.

Figure 4 shows an overhead view of the test compartment after soil excavation to the pipeline following one of the experiments. Because each experiment was run until a total displacement of about 1 m, the analytical models can be tested and calibrated through a broad range of deformation and strain in the elbow. The deformed shape of the pipeline can be seen clearly in the figure. Its shape is remarkably consistent with the shape shown by the finite element simulations discussed in the next section.

**Analytical and Experimental Results**

Finite element analyses were conducted with the HYBRD MODEL to check the ability of the analytical simulations to capture key aspects of the pipeline and elbow response to abrupt lateral displacement. Figure 5a compares the deformed pipeline shape of the analytical model with measured deformation of the experimental pipeline. There is excellent agreement between the two, and there is obvious agreement between the analytical deformation and the overhead view of the deformed pipeline in Figure 4. Figure 5b shows the measured and predicted strains under maximum ground deformation on both the tensile (extrados) and compressive (intrados) surfaces of flexure along the pipeline. Figures 5c and d show the measured and analytical strains around the pipe circumference in which the angular distance is measured from extrados to intrados of pipe, corresponding to 0 and 180°, respectively. In Figure 5d, the data point with an upward arrow indicates the maximum strain measured when the gauge was disconnected during the experiment. Because the disconnection occurred before maximum deformation of the elbow, it is likely that the actual strain was larger than the value plotted. Overall, there is good agreement for both the magnitude and distribution of measured and analytical strains.
The large-scale experiments have provided a rich and comprehensive database for understanding pipeline response to large PGD, particularly under conditions where local constraint at an elbow leads to complex three-dimensional response and high strain concentrations. Although the interpretation of the experimental results is still in progress, the data have already shown that, with appropriate modifications, the current generation of analytical models is able to simulate real performance in a reliable way.

One of the most important aspects of the research has been to clarify the effects of moisture content on the pressures generated by soil-pipeline interaction during PGD. Current analytical models use p-y curves derived from laboratory test results with dry sand. Virtually all sand in the field is placed with measurable water contents that affect its in situ density and shear deformation characteristics. The large-scale experiments have shown that the failure surfaces and deformation patterns in soil adjacent to the pipeline during PGD are significantly different for dry and partially saturated sand.

**Summary**

Large-scale experiments sponsored by Tokyo Gas were successfully completed to evaluate the effects of earthquake-induced ground rupture on welded steel pipelines with elbows. The experimental set-up involved the largest full-scale replication of

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ground deformation effects on pipelines ever simulated in the lab. The tests allow for calibration of a sophisticated soil-pipeline interaction analytical program developed in conjunction with the experimental work. The experimental data and analytical modeling products are of direct relevance for underground gas, water, petroleum, and electrical conduits.

Additional work at Cornell sponsored by Tokyo Gas is planned in the forthcoming year to investigate further the p-y characterization for partially saturated sand as a function a water content and compaction effort. Work also is planned with collaborating universities for developing the next generation of analytical model that will represent the soil as a continuum with specific constitutive relationships capable of simulating large ground deformation and its interaction with buried pipelines.

References


