The U.S. and Japanese case histories represent over 84 years of cumulative observations and analyses of earthquake-induced ground deformation and lifeline response. The case histories include the most important earthquakes which have occurred in the United States and Japan. The 1964 Alaska earthquake, in tandem with the Niigata earthquake of the same year, focused the attention of the engineering community on liquefaction and its devastating effects. These events can be considered as the beginning of the modern era for geotechnical investigations of liquefaction phenomena. The 1971 San Fernando earthquake marks the beginning of concerted research and development pertaining to earthquake effects on lifeline systems, and a major catalyst for the emergence of Lifeline Earthquake Engineering as a distinct and sustainable field of practice. The 1979, 1981, and 1987 earthquakes in the Imperial Valley are a unique combination of seismic events in which recurrent liquefaction figures prominently. Data from this sequence of earthquakes include in-ground measurements of acceleration, pore pressure response, and permanent ground deformation at a site of soil liquefaction. The 1906 San Francisco earthquake is perhaps the most important seismic event in U.S. history. It is of considerable interest to note that the full significance of this event with regard to liquefaction and lifeline systems was realized only after a re-examination of the historical records following the 1964 Alaska and 1971 San Fernando earthquakes. The relevance of the data contained in this case history pertaining to liquefaction-induced lateral spreads, the damage they caused to the water delivery system, and their ultimate contribution to fire in San Francisco was substantiated in full by the events of the 1989 Loma Prieta earthquake. Liquefaction at the same locations as those in 1906 and consequent damage to the water supply brought the City of San Francisco dangerously close to another major conflagration in 1989.

The study of the 1983 Nihonkai-Chubu earthquake was a significant achievement by Japanese researchers working on liquefaction-induced ground displacements and the damage they cause to structures. Large ground dis-

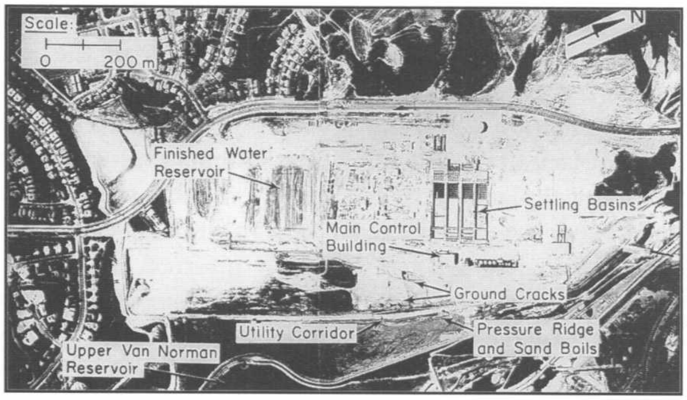


Figure 1
Aerial View of Jensen Filtration Plant

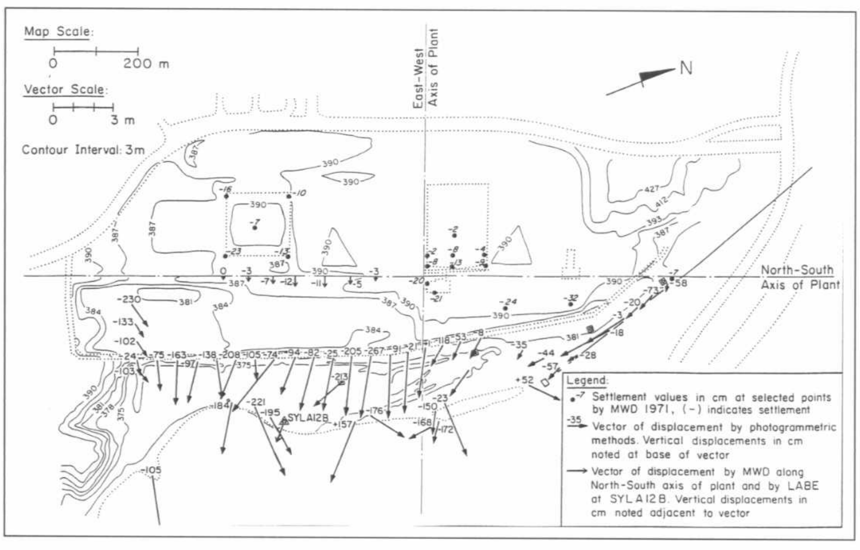
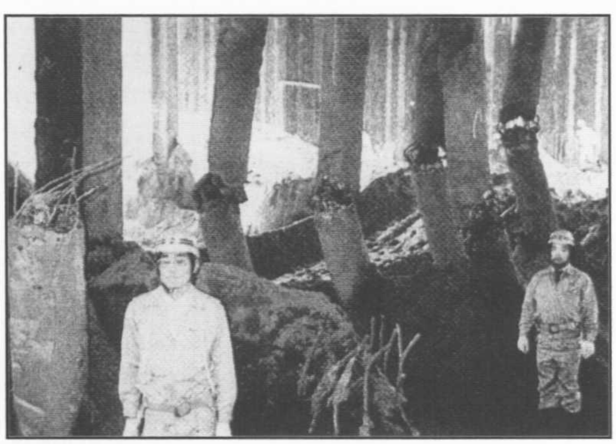


Figure 2
Displacements Caused by Lateral Spread at the Jensen Plant Determined by Photogrametric Analysis

placements of several meters were recorded for the first time through an investigation of damage to buried gas pipes in Noshiro City. The 1923 Kanto earthquake, which severely damaged Metropolitan Tokyo, is one of the most important seismic events in Japanese history. Case histories of the 1923 Kanto and the 1948 Fukui earthquakes provide highly instructive information about liquefaction-induced ground displacement and related structural damage on alluvial plains. This is particularly important since many large Japanese cities are located in similar geological settings. The 1990 Luzon, Philippines earthquake brought soil liquefaction and its related damage to the attention of the Philippine people. In this sense, it was similar to the Japanese situation at the time of the 1964 Niigata earthquake. This earthquake reminded us once again of the severity of liquefaction-induced damage to structures designed and constructed with little or no consideration of such effects.

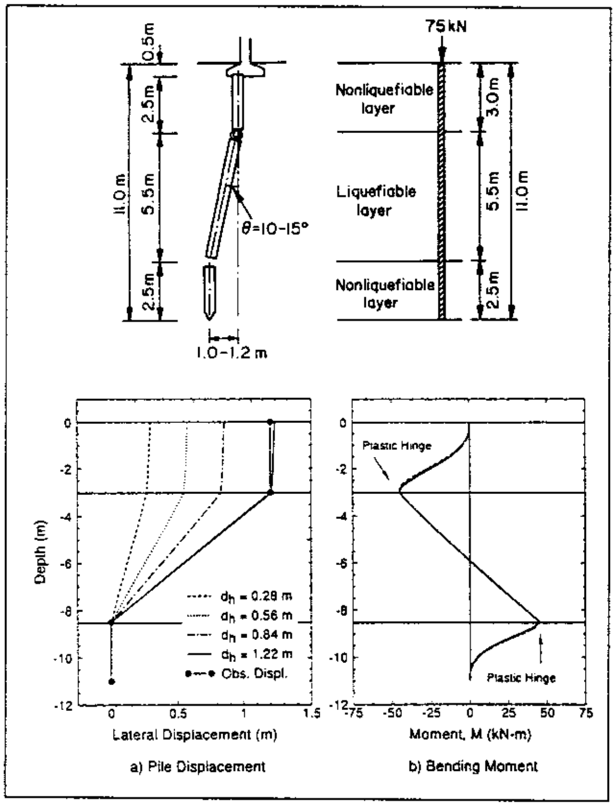
Among the most notable accomplishments of the U.S.-Japan cooperative research is the use of stereo pair air photos before and after an earthquake to perform photogrametric analysis of large ground deformation. This process has literally revolutionized the way engineers and geologists evaluate soil displacements by providing a global view of deformation which allows patterns of distortion to be quantified and related to geologic and topographic characteristics. A noteworthy example of photogrametric analysis involves liquefaction and lateral spreading along the west side of the Upper Van Norman Reservoir during the 1971 San Fernando earthquake. Figure 1 shows an aerial view of the Jensen Filtration Plant on the west side of the reservoir, and figure 2 shows the vectors of lateral ground displacement and settlements evaluated with photogrametric techniques. The lateral displacements were as large as 3 m, about twice as large as had been previously inferred by surface observations. At this location, moreover, there were six different transmission pipelines, conveying water, gas, and oil at high pressures, which were subjected to virtually the same pattern of ground displacement. Both the construction of the lines and distribution of ground movements are well defined. A reliable record of pipeline performance has been developed in which the locations and specific characteristics of damage are described. Moreover, the record of response involves both failed pipelines and those which were able to sustain large differential movement.



■ **Figure 3**
Piles Deformed by Liquefaction-Induced Lateral Spread at the NHK Building in Niigata, Japan (courtesy of S. Kawamura)

The information in this case history is sufficiently detailed to characterize the soil properties, deformation patterns, and pipeline characteristics such that analytical models can be tested against the observations, and the field data used as a basis for verifying or modifying analytical methods.

A major accomplishment of the U.S.-Japan research has been the development of a computer code, B-STRUCT, which provides for material and geometric nonlinear analyses of pipeline and pile foundation response to permanent ground deformation. The program can evaluate the performance of single piles and pile groups. It has been tested successfully against reinforced pile load test data provided by the Daido Concrete Company of Japan and field measurements of pile deformation caused by lateral spread during the 1964 Niigata earthquake. Model validation and refinements are being pursued by means of centrifuge tests performed at Rensselaer Polytechnic Institute.



■ Figure 4
Profile View of Damaged Pile, Soils, and Comparisons of Analytical Results and Field Measurements

Figure 3 shows deformed concrete piles of the NHK Building in Niigata, which were damaged by liquefaction-induced lateral spread. Figure 4 shows a cross-sectional view of a deformed pile and soil conditions underlying the buildings. The pile lateral displacement modeled by B-STRUCT is shown to compare very favorably with the measured pile deformation. Analytical bending moment diagrams show the formation of plastic hinges at the interfaces between the liquefiable and nonliquefiable layers at the upper and lower portions of the pile. These analytical results, which are fully consistent with field measurement, demonstrate the critical importance of the upper nonliquefiable layer in generating lateral force and flexural deformation of the pile which leads to failure.

Conclusion

In summary, the benefits derived from the U.S.-Japan Cooperative Research Program are:

- Coordinated research program, with contributions from 27 U.S. and 38 Japanese institutions. Only an internationally recognized institution, such as NCEER, is capable of organizing and coordinating such a large program.
- Published case history volumes of the most important U.S. and Japanese earthquakes, with comprehensive documentation and measurements of liquefaction-induced ground deformation and lifeline performance.
- Published proceedings of five U.S.-Japan workshops, providing state-of-the-art findings with respect to case history data, analytical and physical modeling of large ground deformations and associated soil-structure interaction, countermeasures against soil liquefaction, and improvements in siting, earthquake resistant design, and retrofitting of lifelines.
- Photogrametric analyses of air photos before and after earthquakes to measure and show global patterns of soil lateral and vertical movement.
- Computer models and codes for analyzing large ground deformation effects on pipelines and pile foundations. Validation and refinements of the models are accomplished through comparison with case history data and centrifuge test results on single piles and pile groups.

Personnel and Institutions

There has been substantial interaction with NCEER researchers, commercial, non-profit, and governmental organizations. Those participating in the project include the University of Arizona, B.C. Gas, Brigham Young University, California Department of Transportation, City University of New York, Cornell University, Dames and Moore, EQE, Inc., Federal Emergency Management Administration, Geomatrix, Harding Lawson Associates, Lamont-Doherty Earth Observatory, National Institute of Science and Technology, Princeton University, Rensselaer Polytechnic Institute, San Francisco Public Works Department, Fire Department, and Water Department, Southern California Gas Company, Stanford University, State University of New York, United States Geological Survey, University of California at Berkeley, Davis, and Los Angeles, University of Southern California, University of Tulsa, and Weidlinger Associates, Inc. Japanese institutions involved in the research include Association for Construction Technology for Concrete Piles, Association for the Development of Earthquake Prediction, Central Research Institute of Electric Power Industry, Chubu Electric Co., Inc., Daido Concrete, Japan Eng. Consultants Co., Ltd., JDC Corporation, Kajima Corporation, Kansai Electric Power Inc., Kiso-Jiban Consultants, Co., Ltd., Kanazawa University, Konoike Construction Co., Ltd., Kumagai Gumi Co., Ltd., Kyoto University, Kyushu Institute of Technology, Niigata University, Nippon Telegraph & Telephone Corp., NKK Corporation, Okumura Corporation, Port & Harbor Research Institute-Ministry of Transportation, Public Works Research Institute-Ministry of Construction, Sato Kogyo Co., Ltd., Shimizu Corporation, Shizuoka Prefectural Government, Taisei Corporation, Takenaka Technical Research Laboratory, Tobishima Corporation, Tohoku Electric Power Co., Inc., Tokai University, Tokyo Denki University, Tokyo Electric Power Company, Tokyo Electric Power Services Co., Ltd., Tokyo Gas Co., Ltd., Tokyo Metropolitan University, University of Tokyo, Waseda University, Yamaguchi University, and Yokohama National University.

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