Proceedings Third UJNR Workshop on Soil-Structure Interaction, March 29-30, 2004, Menlo Park, California, USA.

Large-displacement Facility for Testing Highly Ductile Lifeline Systems

Scott L. Jones,[a] Keith E. Kesner,[a] Thomas D. O'Rourke,[a] Harry E. Stewart,[a] Tarek Abdoun,[b] and Michael J. O'Rourke [b]

Innovative testing facilities are being constructed at Cornell University and Rensselaer Polytechnic Institute (RPI) as part of Phase 2 of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) of the National Science Foundation. The project will develop advanced simulation and experimental evaluation of key lifeline components under earthquake conditions. This paper describes the experimental facilities, as well as the problems of soil-structure interaction and above-ground structural response that can be addressed through physical simulation with the facilities. Issues associated with rate of ground rupture, angle of intersection between buried lifeline and ground displacement planes, and size of the facility also are treated. The paper explores the use of full- and near-full-scale simulations at Cornell combined with centrifuge experiments at RPI to cover a broad range of sizes, geometries, and time rate effects on the performance of lifelines in the field.

INTRODUCTION

Lifeline systems are essential for civil infrastructure because they deliver the resources and services needed to sustain a modern community. Lifelines are often grouped into six principal systems: electric power, gas and liquid fuels, telecommunications, transportation, wastewater facilities, and water supply. When an earthquake strikes, life and property are threatened in the short term when functional water supply, transportation systems, electric power, and telecommunications either fail or lose their capabilities during emergency operations. In the long term, earthquake recovery is prolonged, especially when significant construction is required to rehabilitate damaged facilities.

---

[a] School of Civil and Environmental Engineering, 220 Hollister Hall, Cornell University, Ithaca, NY 14853
[b] Department of Civil and Environmental Engineering, JEC 4049, Rensselaer Polytechnic Institute, Troy, NY 12180

There is a compelling need in the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) for experimental and testing facilities to evaluate lifeline earthquake behavior. Not only are experimental facilities required for investigating the aboveground response of structures, such as viaducts and bridges, but equipment is needed to investigate the soil-structure interaction of underground lifeline components. In congested urban and suburban environments, large portions of lifeline systems are buried or constructed underground. Understanding how ground deformation affects buried lifelines, therefore, is a critical aspect of earthquake engineering, which needs to be addressed in NEES by advanced laboratory experiments and computational modeling.

The remainder of this paper describes the experimental facilities at Cornell University that were developed specifically for the NEES project and some examples of research projects that might be undertaken at the Cornell NEES facility.

EXPERIMENTAL FACILITIES

The NEES equipment will be housed primarily in the George Winter Civil Infrastructure Laboratory at Cornell University, with complementary equipment being housed in the Centrifuge Facility at Rensselaer Polytechnic Institute (RPI). Figure 1 provides an expanded view of the existing Winter Lab highbay within which elements of the NEES equipment system are shown along with some possible experimental layouts. The strong walls are modular and can be assembled for a maximum 17-m length for the low wall and 7.2-m height for the high wall. There will be two 0.91-m actuators and one 0.63-m actuator. Soil will be stored in special bins recessed into the walls to conserve space. Room is available for supplemental soil storage in the high bay should a future experiment require additional volumes of soil. A portable conveyor system provides rapid movement and placement of soil. Nominal soil test boxes are shown. The dimensions of the boxes need to be chosen according to the purpose and type of experiment. Room is available for boxes as long as 20m. A nominal bending test on pressurized pipe is also shown. The vertical reaction frames shown in Figure 1 are not a part of the NEES equipment but may be provided depending on availability of funds as the project draws to a close. The remainder of this section provides a summary of the NEES equipment and its performance specifications (Tables 1-5).

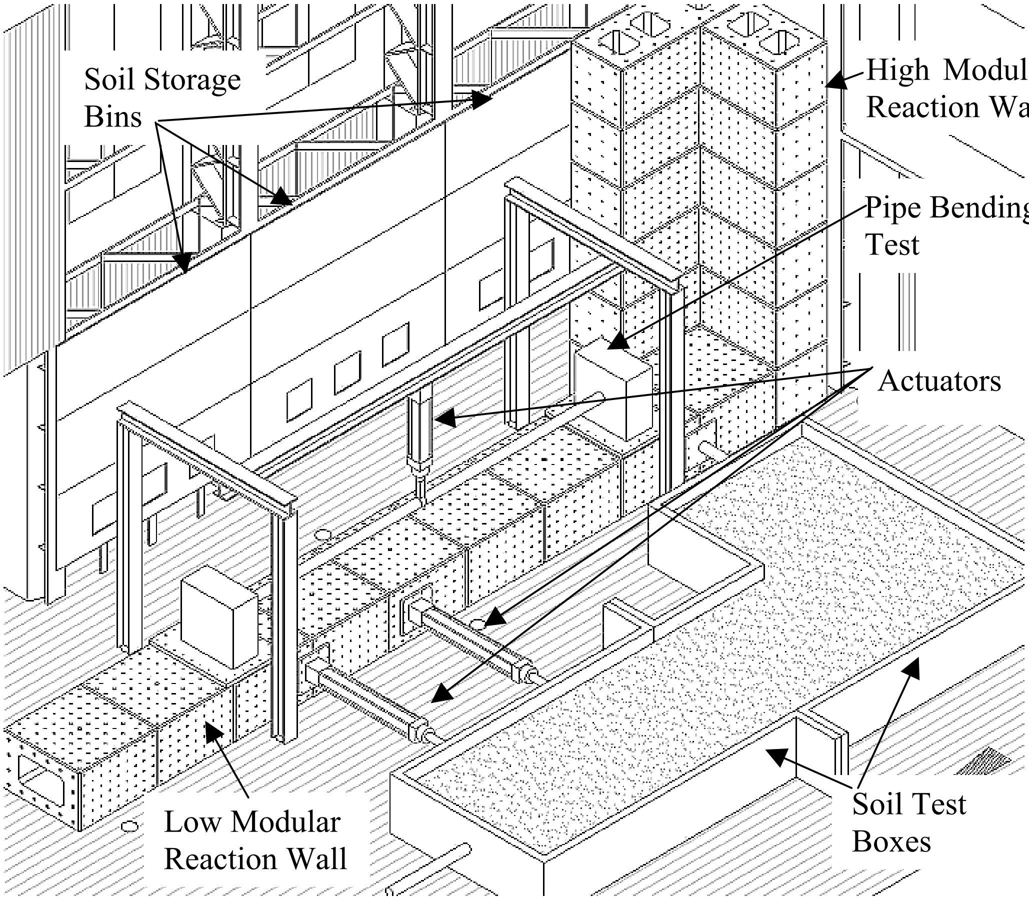


Figure 1. Perspective View of George Winter Infrastructure Laboratory Highbay with NEES Equipment in Place.

LARGE-DISPLACEMENT ACTUATORS AND SERVO-HYDRAULICS

Servo-hydraulic actuators and ancillary hydraulic equipment are necessary to support large-displacement physical testing for lifeline systems. Recent testing at Cornell in collaboration with Tokyo Gas has involved the largest laboratory tests ever performed of pipeline response to permanent ground deformation to improve design and siting procedures for steel pipelines with elbows (Yoshizaki et al. 2003). The motions imposed on the test system were on the order of a meter so that full soil-structure interaction could be mobilized. Multiple actuators with one-way strokes on the order of 2m will provide unique testing equipment that can be used on a very wide range of buried and above-ground lifeline systems. These actuators and supporting hydraulic equipment will provide state-of-the-art systems not available at other experimental locations.

In addition to the ability to test large-scale structures, material tests can be performed using hydraulic wedge grips. The grips can be used for testing of materials ranging from brittle matrix composites to geo-textiles to ductile steel coupons. Up to a 220 kN tensile

Table 1. Servo-Hydraulics Performance Specifications

Large-Displacement Actuators and Servo-Hydraulics	Performance Specification
Linear Hydraulic Actuators	Two actuators with load capacities of 295 kN tension, 498 kN compression, strokes of +/- 0.91 meters. One actuator with load capacity of 445 kN tension, 649 kN compression, stroke of +/- 0.63 m.
Hydraulic Power Supplies	Servovalves, manifolds, and pump with flow rates and capacities for large actuator movements and simultaneous use of multiple actuators.
Electronic Controls	Independent control of either load or displacement on multiple actuators in simultaneous use.
Hydraulic Wedge Grips	Apply up to 220 kN tension to gripped material while ensuring a true alignment of axial force; grips should not slip in the direction of loading.

force can be applied to gripped material while ensuring true alignment of the tensile force. Installation of the grips in a 900 kN four post (approximately 1.5 m high) test frame (+/- 75 mm displacement) will allow for testing of large-scale tensile specimens to high strain levels. The hydraulic grips are an essential component in the development of new materials for lifelines.

DATA ACQUISITION AND SENSORS

Upgraded high-speed data acquisition systems will be assembled using a variety of components. Two Pentium 4 computers will be interfaced with high-speed multiplexers, signal conditioners, and data converter boards. The data acquisition systems will be interfaced with the servo-hydraulic system controls and connected to the Internet. The main sensors consist of an advanced fiber-optic signal conditioning unit and large-stroke displacement transducers. The fiber optic instrumentation consists of a high-resolution, high-precision system. This is a high-speed sensor conditioner that can adapt to slow or fast testing (sampling rates up to 1000Hz). All data acquisition systems will be capable of multi-channel measurements of temperature, pressure, force, displacement, or strain using a common sensor-conditioning unit with interchangeable sensors. Magneto-strictive displacement measuring devices with 2-m ranges also will be used. These devices are a necessary measuring tool for large-displacement soil-foundation-structure interaction (SFSI) testing.

Table 2. Data Acquisition Performance Specifications

Data Acquisition Systems	Performance Specification
Computers	High-speed, large storage capacity, Internet connectivity
A/D boards. Multiplexers	16-bit resolution, expandable for 128 to 256 data channels
Signal Conditioning	Stable power supply; low noise; independent variable gain; capable of using a wide variety of transducers
Sensors	Large displacement (up to 2 m), precision and accuracy, compatibility with signal conditioning and other control systems, fiber-optic system capable of measuring strains up to 5000 to 10000 microstrain, laser extensometers for large displacement measurements.

MODULAR REACTION WALLS

Experiments on lifelines can be performed in numerous ways using a segmentally precast, post-tensioned concrete strong wall/floor assembly. The baseline assembly would be made up of a long, low segmental box girder along the existing lab floor with modular high walls perpendicular to each other and forming a corner on one end (see Figure 5). The low box segments would form a maximum length of 17 m off of which the soil box experiments

Table 3. Modular Reaction Wall Performance Specifications

Modular Reaction Walls	Performance Specification
Low strong wall/box	Must resist lateral loads of 675 kN locally and 1350 kN overall anywhere along the height; must resist local vertical loads of 900 kN; must be match-cast, precast so as to be easily post-tensioned to form a long, low wall and be stackable for storage; each segment must weigh less than 89 kN to use existing overhead crane; must be hollow to allow for access from within; must be able to post-tension to both high walls.
High strong walls	Must resist lateral loads of 900 kN at a height of 5m from a fixed base; must resist vertical tensile/compressive loads of 1800 kN; must be able to post-tension to the low strong wall/box in two directions; must be able to post-tension to perpendicular high strong wall to facilitate lateral loading in two directions.
Floor anchor system	The combination of existing 900 kN floor anchors and 14 supplemental 670 kN floor anchors can be used to anchor reaction frames, test specimens and strong wall components to the existing structure.

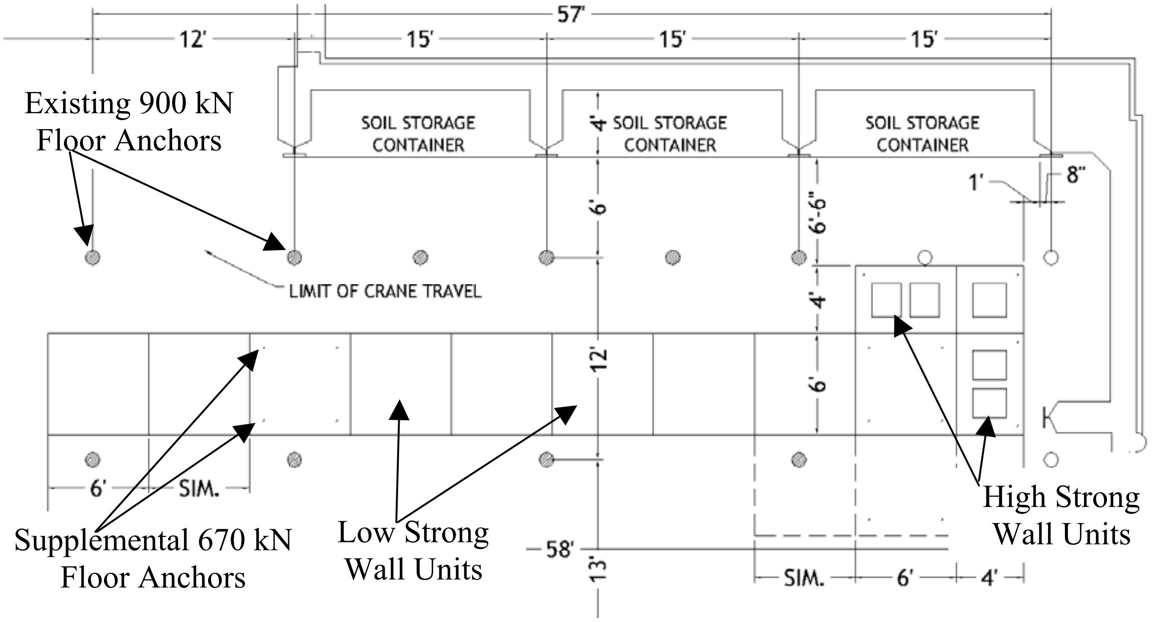


Figure 2. Plan View of Modular Strong Wall System for Large-displacement Lifeline Experiments

on buried lifelines will react. Simple extension of the low strong wall to include two narrow high walls at one end broadens the possibilities of shared use of the proposed NEES site. The top surface of the low wall will be used for a variety of above-ground lifeline testing including highway component and system testing as well as structural pipe testing prior to the soil-structure interaction tests. On this surface, vertical loads can be applied to bridge girders, substructure components and bridge connections. In the raised wall portion of the assembly these components and systems can be tested with lateral loads in two directions. Vertical loads can be supported off of the low wall acting as a strong floor or off of the high walls through an attached load frame. Experiments on the top surface of the low wall can take place without interfering with the floor space where the soil box experiments would be set up. In addition, when the floor space is not being used for soil box experiments, various structural configurations can be tested under lateral loads laying flat. A limited version of this arrangement was recently used in the Winter Lab for the research on unbonded post-tensioned concrete columns. Finally, the low wall could be built in two parts with portions of the high walls stacked on the inside of the openings to form abutments. These two abutments could then be used as reaction walls to conduct soil-structure interaction experiments in an axial configuration. To join the reaction wall components to the existing floor a combination of existing 900 kN floor anchors and 14 supplemental 670 kN anchors are used. The 14 supplemental anchors were specifically added to anchor reaction wall components. Eight of

Table 4. Soil Storage Performance Specifications

Soil-Storage	Performance Specification
Soil Bins	On-site storage of on the order of 50 to 55 m^3 of soil used in large-scale movable split soil boxes. The bins are loaded through the open top and unloaded using sliding gates at the bottom. Inside storage for moisture control and to avoid freezing. Minimize internal use of floor space in crane bay.
Conveyor System	2 conveyors with a 61 m/min belt speed capable of moving approximately 19 m^3 of soil per hour: 1 4.5 m long with a 3 m lift, 1 6.7 m long with a 4.5 m lift. Portability. Flexible configurations.

the anchors arranged in groups to anchor both ends of the low wall sections. Four of the anchors are used in the high wall section to resist over-turning. The remaining two anchors are used to anchor alternate locations for the low wall sections.

SOIL STORAGE AND CONVEYANCE

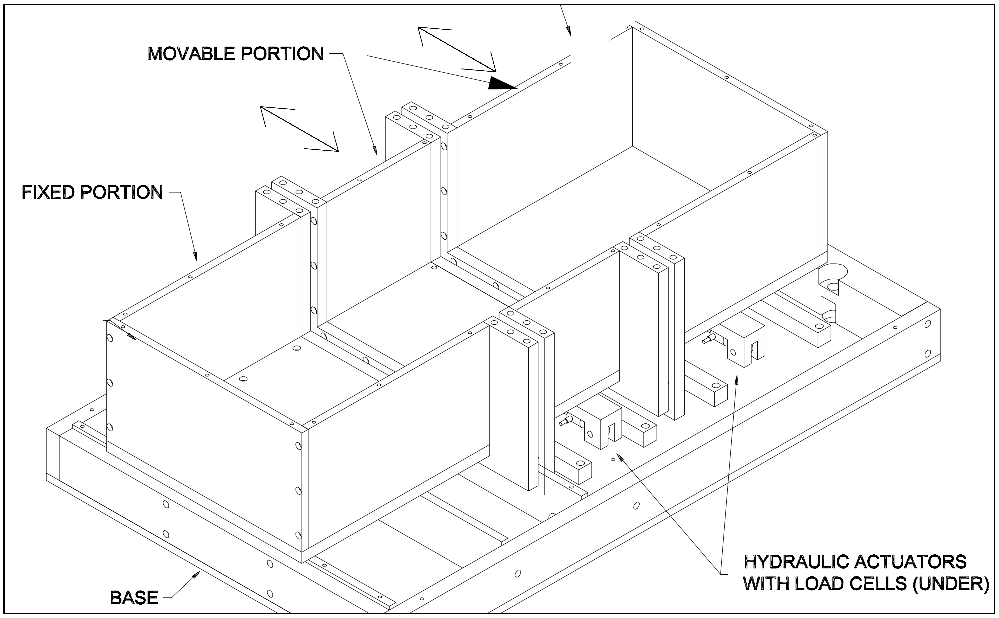
A soil storage system capable of holding and handling large quantities of soil for full-scale and near full-scale soil-structure interaction experiments on pipelines and bridge systems has been constructed in the crane bay area of the Winter Lab. The crane bay has 5.5 m high, 0.3-m-thick concrete walls spanning the 4.5 m horizontal distances between heavy, laced, concrete jacketed columns that support the roof. The columns are jacketed for their lower 5.5 m and unjacketed for the remaining 6.7 m. Steel beams with an exposed flange were cast into the concrete columns. The flanges are used to connect other structural members to the columns. The columns are approximately 1.2 m deep and there is approximately 4 m between the inner edges of any two adjacent columns. This volume is reduced in the lower portions of the units because of the tapered sections. Reinforced steel plating has been placed between the inner steel flanges of adjacent columns to create the basic storage unit. A conveyor belt assembly with a cleated belt trough slider bed belt will be used to charge the soil bins. The front of the soil storage containment bins has sliding steel discharge panels. Discharged soil will be moved with an existing small Bobcat loader, a trip-release concrete bucket and overhead crane, or the conveyor belts.

Table 5. Centrifuge Containers Performance Specifications

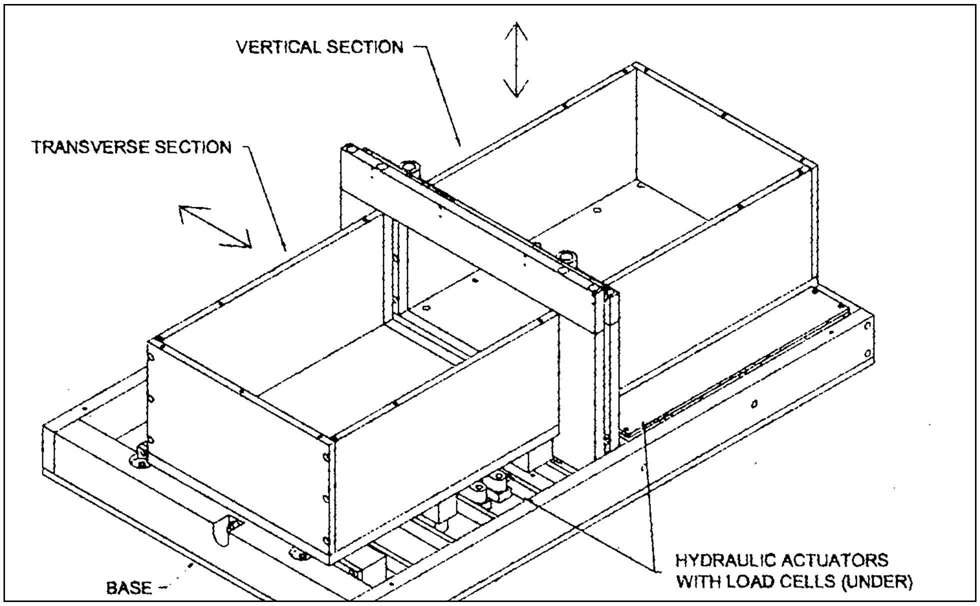
Centrifuge Containers	Performance Specification
Split Boxes	Overall dimensions:108 cm L x 69 cm W x 36 cm H; Inside container dimensions: Model dimensions of 100 cm L x 36 cm W x 20 cm H; Prototype dimensions at 75g of 75m x 27m x 15m Empty weight of 900 N Displacement of movable sections = 0 to 8 cm Operating hydraulic pressure = 8.3 MPa Maximum Actuator force = 8.9 kN 1 box with 2 sections—1 capable of vertical movement, capable of horizontal movement 1 box with 3 sections—2 capable of horizontal movement

CENTRIFUGE CONTAINERS

The containers at the RPI centrifuge will use two hydraulic cylinders to produce localized shear strains along one or two vertical interfaces in a soil model while being spun at centrifugal accelerations of up to75g. Load cells directly connected between each actuator and the movable portions of the container measure the shearing force applied by the actuators. The maximum achievable displacement is 8 cm (6m prototype units). Motion of each actuator is precisely controlled using a servo-valve and feedback control system. Using a function generator or computer equipped with a DAC interface board, a variety of input strain distributions and time histories can be created. The containers will be manufactured from high-strength aluminum alloy. The moving portions of the container are supported and guided using roller bearings to provide precise movement with minimal friction. The sliding interface between the fixed and movable portions of the container utilizes low-friction Teflon seals protected by steel shields. When used with a suitable Teflon sheet liner, this design effectively excludes soil from the interface, maximizing the service life of the seals. One container (Figure 3a) will have three sections having two actuators and a two-channel displacement control system. In this concept, one section will be fixed, and either one or both of the other sections can be moved. If two sections are moved, they can be moved either together or independently. In this way a wide variety of strain configurations can be modeled. The other container (Figure 3b) will have two sections having two actuators and a two-channel displacement control system. In this concept, one section can be moved



(a) 1 fixed segment, two segments capable of independent horizontal movement.



(b) 1 segment capable of independent vertical movement, 1 segment capable of independent horizontal movement

Figure 3. Schematic Diagram of Split Soil Containers for Use with the Centrifuge at RPI.

horizontally and the other can be moved vertically, allowing for experiments on pipes experiencing either horizontal, vertical, or both horizontal and vertical PGD.

ADDITIONAL TESTING EQUIPMENT

Figure 1 also shows several pieces of testing equipment that are not included in the construction of the NEES facility at Cornell University—the most important of which are the split test boxes and the vertical reaction frame.

The split boxes have traditionally been built by reinforcing a plywood box with steel framing and resting the bottom beams of the moving box on Teflon strips to minimize friction. Steel will often be available in the Winter Lab for framing of the split boxes but the researchers using the facility are responsible for surveying the website (www.nees.cornell.edu) and coordinating with the NEES Operations Manager at Cornell University to determine the availability of steel beams. The website and/or Operations Manager will also be helpful for identifying local fabricators and distributors who can provide steel framing and Teflon.

A vertical reaction frame is anticipated to be an essential piece of testing equipment for a number of applications: applying gravity load to structural members, applying bending loads to pipes, etc. The current plans are to provide a vertical reaction frame capable of resisting up to approximately 1 MN of force, pending a review of cost-savings on other equipment. The original budget did not include an allowance for a vertical reaction frame. Again, researchers should review the website and/or contact the NEES Operations Manager at Cornell University to determine the availability of and specifications for a vertical reaction frame.

In addition to the testing equipment described in the previous two paragraphs, researchers will be responsible for providing one-time measuring devices, such as strain gauges and fiber-optic gauges, and whatever soil they may want to use for testing. Guidelines will be available on the Cornell NEES website or through the Operations Manager.

POTENTIAL RESEARCH PROJECTS

The NEES facility at Cornell University and RPI has been designed to address several classes of research projects not covered by the other equipment sites in NEES. One project class in particular (soil-structure interaction under permanent ground deformation) has been prominent in planning the facility and is discussed in detail below. Other complementary project classes are briefly described in the following subsections.

SOIL-STRUCTURE INTERACTION UNDER PERMANENT GROUND DEFORMATION

It has long been recognized that the most serious damage to underground lifelines during an earthquake is caused by PGD (e.g., O'Rourke 1998). It is not possible to model with accuracy the soil displacement patterns at all potentially vulnerable locations. In fact, studies of ground deformation patterns associated with surface faulting have shown complex patterns of ground rupture and distributed deformation even for strike slip faults (Bray et al. 1994, Lazarte et al. 1994). It is possible, nevertheless, to set an upper bound on deformation effects by simplifying spatially distributed PGD as movement concentrated along planes of soil failure. Detailed studies of fault deformation disclose that abrupt soil rupture and offsets are indeed recurrent patterns of deformation (Bray 2001). Accordingly, they establish a baseline with which to evaluate soil-lifeline interaction under large ground deformation.

Figure 4 illustrates the principal modes of soil-structure interaction under PGD. Figure 4a shows pipelines crossing a fault plane subjected to oblique slip. Reverse and normal faults tend to promote compression and tension, respectively. Strike slip may induce compression

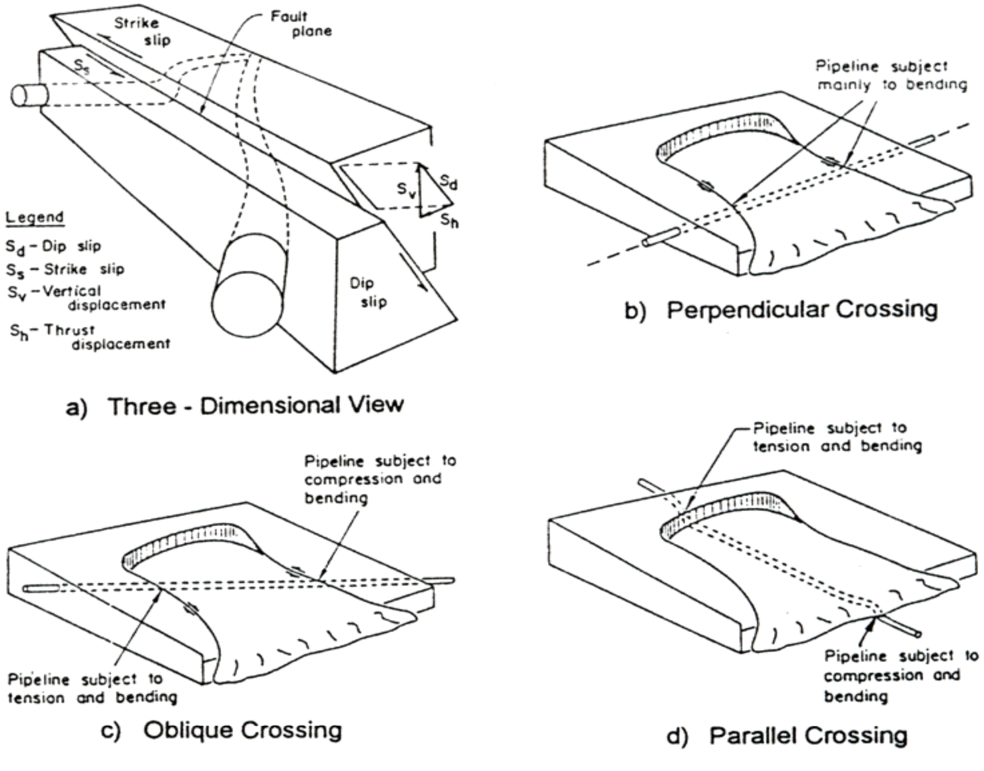


Figure 4. Soil-Pipeline Interaction Triggered by Earthquake-Induced PGD (after O'Rourke, 1998).

or tension, depending on the angle of intersection between the pipeline and fault. As shown in Figs. 4b and c, the pipeline will undergo bending and either tension or compression at the margins of a slide where the deformation is similar to that at an oblique fault crossing. The ground deformation at the head of the slide (Fig. 4d) is similar to normal faulting, where the pipeline is subject to combined bending and tensile strain. At the toe of the slide (Fig. 4d), the ground deformation is similar to reverse faulting, producing compressive strains in the pipeline.

A number of approaches have been proposed to address the problem of lifeline response to abrupt soil movement. Newmark and Hall (1975), for example, developed one of the first analytical models for a pipeline intersecting a strike-slip fault at an angle, such that ground rupture results primarily in pipe tensile strain. They assumed the pipe is firmly attached to the soil (i.e., no relative pipeline displacement) at two anchor points some distance from the fault trace and neglected the pipeline bending stiffness and horizontal interactions between soil and pipe.

Kennedy et al. (1977) extended the ideas of Newmark and Hall by considering the effects of lateral interaction. They also considered the influence of large axial strains on pipeline bending stiffness, and modeled pipeline flexure.

Subsequent to the Kennedy et al. work, Wang and Yeh (1985) suggested modifications to the closed form analytical model, while Ariman and Lee (1991) and Meyersohn (1991) present results from FE models. An independent comparison of the results of the available analytical approaches, as reported in O'Rourke and Liu (1999), suggest that the Kennedy et al. model for strike slip faulting provides the best match to ABAQUS finite element results.

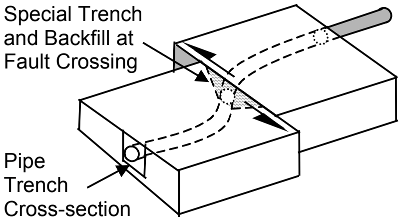
Relatively little analytical work is available for a pipeline crossing a normal or reverse fault. For a normal fault, the pipe–soil system is no longer symmetric, and the transverse interaction force at the pipe-soil interface for downward pipe movement is much larger than that for upward movement. For a pipeline at a reverse fault, it appears that no analytical approach is currently available. The ASCE Guidelines (1984) suggest using the FE method. The behavior for both reverse and normal faulting is difficult to generalize, in part because there are two angles of intersection (the angle in plan between the fault and the pipeline, as well as the dip angle of the fault) in addition to the aforementioned asymmetric nature of the soil resistance in the vertical plane.

The existing analytical approaches are primarily directed at relatively small diameter-to-thickness ratios (D/t) common in the gas and liquid fuel industries. For larger D/t, additional complications are introduced. Ovaling behavior (i.e., the original circular pipe cross-section deforms into an oval) now becomes a design consideration, and modeling procedures become important. For FE analysis at low D/t, the pipe is frequently subdivided into elements, typically about two pipe diameters in length. These pipe elements are connected at nodes where a single axial/longitudinal soil spring and two transverse soil springs are attached. However, for high D/t pipe, which may be susceptible to ovaling, a number of shell elements, distributed around the pipe circumference would be needed. In addition, longitudinal and transverse soil springs need to be attached in some manner to the nodes which connect the individual shell elements.

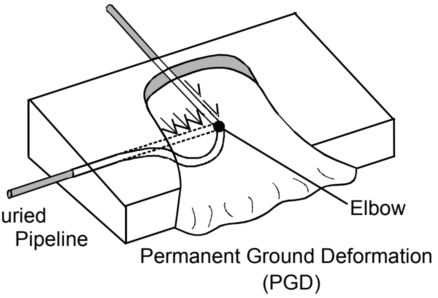
Lack of fundamental knowledge about soil-pipeline interaction and reliance on analytical simplifications result in a current state of practice characterized by a high degree of uncertainty and the absence of design codes and in-depth guidelines. The opportunity for a true breakthrough is therefore available with the NEES equipment sites at CU and RPI. Furthermore, this breakthrough would have a profound, positive influence on the design and construction of widespread critical facilities affecting public safety and security.

To address this very important problem, research can be performed using the combined resources of the Cornell Large Displacement Lifeline Testing Facility and the RPI 150 g-ton Geotechnical Centrifuge in combination with advanced computational simulation. Figure 5 illustrates the concept of split-box testing, which provides the basis for laboratory simulation of the most severe PGD effects associated with surface faulting, liquefaction-induced lateral spread, and landslides.

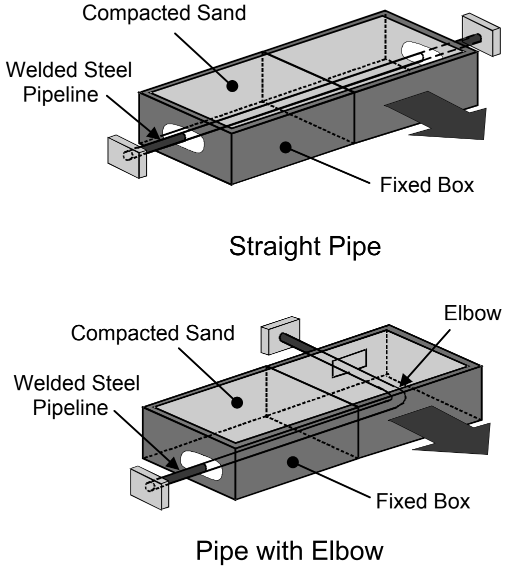
The laboratory and centrifuge equipment have the capability of imposing abrupt soil displacements on buried lifelines consistent with PGD effects at fault crossings and the margins of lateral spreads and landslides. As shown in Figure 5, relative displacement is generated along a moveable interface between two test basins, or boxes, containing soil and the buried lifeline. The lifeline is buried in soil that is placed and compacted according to field construction practice. The scale of the experimental boxes is selected based on computational modeling and previous test experience in an effort to minimize the effect that



a) PGD Effect on Buried Pipelines



b) PGD Effect on Pipelines with Elbows



c) Experimental Concepts

Figure 5. Simulation of Ground Rupture Effects on Lifelines by Split-Box Tests.

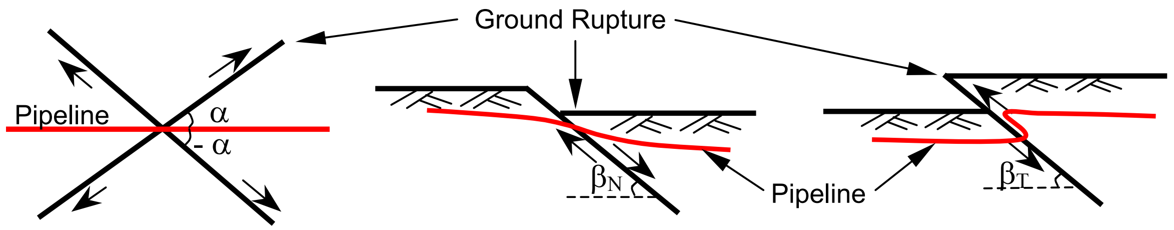
the boundaries of the test facility have on the soil-structure interaction. The experimental facilities will have the capability of imposing horizontal movement and vertical displacement.

The CU facility provides for full-scale testing that concentrates on detailed soil-structure interaction. It permits accurate representation of both the soil and buried lifeline in the vicinity of ground rupture where it is most important to duplicate pipe and soil material behavior and the intricacies of soil-pipeline reactions. The size of the test facility, however, is constrained by the practicalities of large-scale test box construction, soil placement, and actuator load capacity. The RPI facility provides an excellent complement. Through multi-g scaling, larger prototype dimensions and rates of loading can be tested. Soil-structure interaction can be evaluated in considerable detail, although not to the same degree as is possible with the large-scale facility. At both the CU and RPI equipment sites, the prototype lifeline length is influenced by the maximum length of the split box used to simulate ground rupture. Figure 6 shows generic types of ground rupture patterns that have impact for buried lifelines. Table 6 summarizes the characteristics of each facility with respect to size of pipeline/conduit that can be tested, geometry of ground deformation (as depicted in Fig. 6), depth of pipe burial, and total length of pipeline.

Table 6 NEES Site Simulation Capabilities for Soil Lifeline Interaction

Parameter[1]	Cornell NEES Site	RPI NEES Site
Diameter, D	100-600 mm	200-5000 mm
Diameter to Thickness Ratio, D/t	10-120	10-250
Depth of Burial	0.6-1.5 m	0.6-20 m
Maximum Length of Pipeline[2]	18 m	46 m
Pipeline Intersection Angle for Horizontal Deformation, α	+30° to 90° 90° to -30°	62° to 90° 90° to -62°
Normal Deformation Angle, β_N	30° to -90°	90°
Thrust Deformation Angle, β_T	$\leq 30^{\circ}$	NA
Maximum Displacement	1.8 m	4.0 m
Maximum Rate of Displacement	0.1 m/s	0.9 m/s

1 refers to prototype or actual field scale
2 refers to actual test box dimensions; the effective pipeline length can be increased experimentally through the use of actuators in the Cornell facility and special springs in the Rensselaer split box
NA – not available



a) Horizontal Deformation Angle, α (Plan View)

b) Normal Deformation Angle, β_N (cross-section)

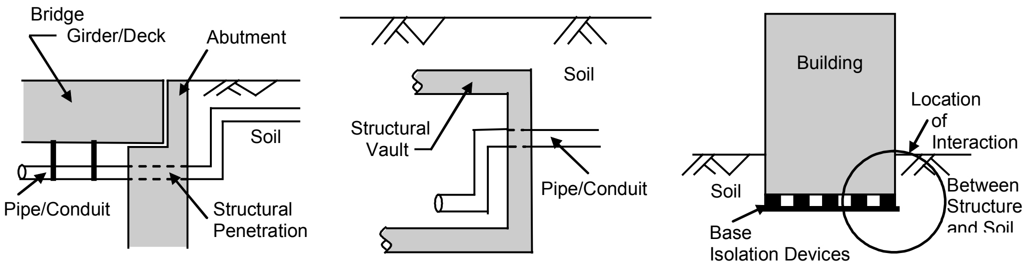
c) Thrust Deformation Angle, β_T (cross-section)

Figure 6. Abrupt Ground Rupture Pattern for Experimental and Numerical Investigations

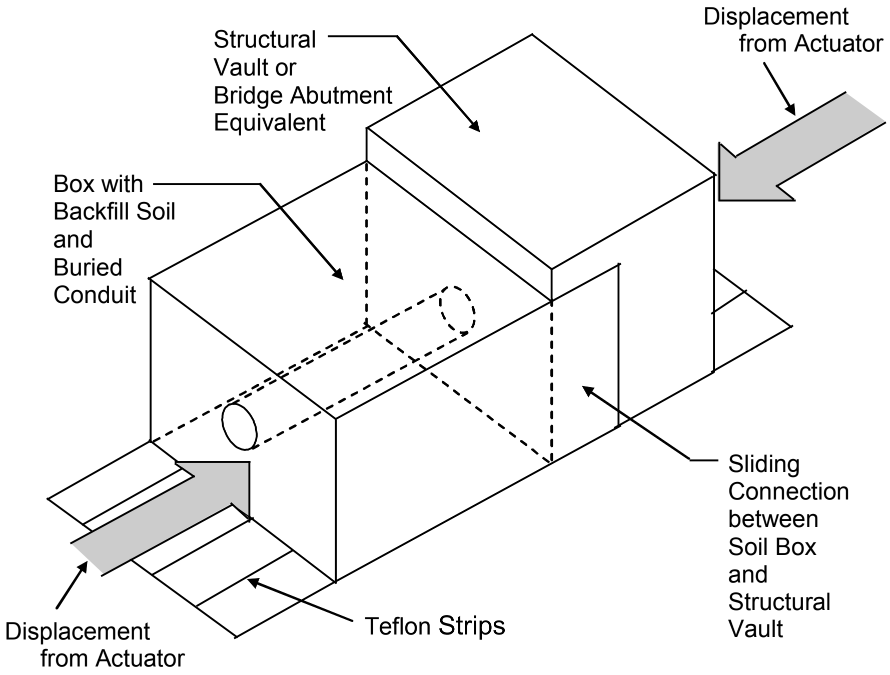
There are three principal types of ground rupture patterns that are illustrated schematically in Fig. 6: a) horizontal deformation, corresponding to strike slip displacement; b) normal deformation, corresponding to normal faulting; and c) thrust deformation, corresponding to thrust and reverse faulting. Combinations of a) with b) or c) are also possible.

SOIL-STRUCTURE INTERFACE INTERACTIONS

Soil-structure interface problems involve locations where abrupt transitions from structure to soil create localized stresses and deformations. As illustrated in Figure 7, examples include bridge abutments where a number of different cables and conduits may transition from soil through the abutment and/or other structural elements. Additional examples include basement and vault penetrations of cable and conduits. At these locations, transient motion of the structure and adjacent soil can be significantly out of phase. Furthermore, settlement can occur in the adjacent soil, thereby imposing permanent ground deformation at the same time transient movements take place. Penetrations of structural



a) Bridges b) Vaults c) Base Isolation



d) Experimental Concept

Figure 7. Soil-Structure Interface Interactions

walls and abutments have been identified as one of the most important issues for the earthquake resistant design of lifelines (e.g., ASCE 1984).

This experimental facility will have the ability to simulate complex interactions at soil-structure interfaces. The experimental concept is shown in Figure 2d. An actuator can apply lateral displacements to a structural vault or bridge abutment element at the same time another actuator applies displacements to a test box with backfill soil and a buried conduit that penetrates the structural element. A special sliding connection can be fabricated to allow relative movement between the test box and structural element. Teflon strips will allow for low-friction sliding of the experimental members.

ACKNOWLEDGEMENTS

We would like to acknowledge Nathaniel A. Olson for creating all of the CAD drawings of the modular reaction wall.

This work was supported in part by the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program of the National Science Foundation under Award Number CMS-0217366.

REFERENCES

American Society of Civil Engineering (ASCE), 1984, *Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*, Committee on Gas and Liquid Fuel Lifelines, Reston, VA.

Ariman, T. and Lee, B.J., 1991, Tension/bending behavior of buried pipelines under large ground deformation in active faults, *Proceedings of the Third U.S. Conference on Lifeline Earthquake Engineering*, Technical Council on Lifeline Earthquake Engineering, Monograph No. 4, ASCE, 226-233.

Bray, J. D., 2001, Developing mitigation measures for the hazards associated with earthquake Surface fault rupture,” *Workshop on Seismic Fault-Induced Failures: Possible Remedies for Damage to Urban Facilities*, Research Project 2000 Grant-in-Aid for Scientific Research (No. 12355020), Japan Society for the Promotion of Science, Workshop Leader, Kazuo Konagai, University of Tokyo, Japan, January 11-12, 55-79.

Bray, J.D., Seed, R.B., Cluff, L.S., and Seed, H.B., 1994, Earthquake fault rupture propagation through soil, *Journal of Geotechnical Engineering*, ASCE, **120**(3), 543-561.

Kennedy, R.P., Chow, A.W., and Williamson, R.A., 1977, Fault movement effects on buried oil pipeline, *Journal of the Transportation Engineering Division*, ASCE, **103** (TE5), 617-633.

Lazarte, C.A., Bray, J.D., Johnson, A.M., and Lemmer, R.E., 1994, Surface breakage of the 1992 Landers earthquake and its effects on structures, *Bulletin of the Seismological Society of America*, **84**(3), 547-561.

Meyersohn, W.D., 1991, *Analytical and Design Considerations for the Seismic Response of Buried Pipelines*, M.S. Thesis, Cornell University.

Newmark, N.M. and Hall, W.J., 1975, Pipeline design to resist large fault displacement, *Proceedings U.S. National Conference on Earthquake Engineering*, Ann Arbor, Michigan, 416-425.

O'Rourke, M.J. and Liu, X., 1999, *Response of Buried Pipelines Subject to Earthquake Effects*, Monograph No. 3, MCEER, Buffalo, NY.

O'Rourke, T.D., 1998, An overview of geotechnical and lifeline earthquake engineering, *Geotechnical Special Publication No. 75*, ASCE, Reston, VA.

Wang, L.R.L. and Yeh, Y., 1985, A refined seismic analysis and design of buried pipeline for fault movement, *Journal of Earthquake Engineering and Structural Dynamics*, **13**, 75-96.

Yoshizaki, K., O'Rourke, T.D., and Hamada, M., 2003, Large-scale experiments of buried steel pipelines with elbows subjected to permanent ground deformation, *Structural Engineering/Earthquake Engineering*, JSCE **20**(1), 1s-11s.