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Experimental Investigation of Seismic Loading Effect on Soil-Pipe Interface Friction

C. Jiang
University of Dayton, Dept. of Civil and Environmental Engineering,
300 College Park, Dayton, Ohio 45469-0243, U.S.A. jiangc5@udayton.edu

Ö. Bilgin
University of Dayton, Dept. of Civil and Environmental Engineering,
300 College Park, Dayton, Ohio 45469-0243, U.S.A. bilgin@udayton.edu

ABSTRACT: Soil-pipe interface shear strength is important to determine pipe's pullout capacity. The interface friction provide resistance to axial movements when a pipe is exposed to axial loads, such as from temperature changes. Evaluating the interface behaviour between buried pipelines and surrounding soil exposed to seismic loading and vibrations is essential for understanding the pipe-soil interaction mechanisms. Small scale laboratory tests were performed to investigate the changes in soil-pipe interface shear strength due to seismic loading and vibrations. A soil box was built and used for the pipe pullout tests. The box was placed on a shake table which provided the dynamic loading causing vibrations. For the tests, a polyvinyl chloride (PVC) pipe and sand were used. For each test condition, pipe pullout tests were performed before and after a pipe is exposed to seismic vibrations. Key parameters such as peak interface shear strength, displacements at the peak strength, and interface friction angles were investigated for pre- and post-shaking conditions. Several tests under same conditions were also performed to evaluate the repeatability of tests conducted. The test results indicated that the shear strength at the pipe-soil interface can be affected significantly due to an exposure to seismic vibrations. This paper presents the physical model built and used for the tests, results obtained, and findings of the study.

1 INTRODUCTION

Buried pipelines are vital for transporting water, gas, and other utilities, and their performance during earthquakes is critical for infrastructure resilience. When subjected to seismic loading, relative movements may develop between the pipe and surrounding soil, and the resistance to these movements mainly depends on the soil–pipe interface friction.

Previous research has investigated the pullout and lateral response of buried pipelines under monotonic loading conditions. Early experimental studies established fundamental relationships between soil resistance and pipe displacement, providing the basis for understanding soil–pipe interaction mechanisms (Audibert and Nyman, 1977; Trautmann and O'Rourke, 1985). Subsequent studies expanded this understanding by examining material properties and interface characteristics, including design-oriented evaluations of interface shear resistance for polyethylene pipes (Bilgin and Stewart, 2009). Physical and numerical modeling approaches have also been employed to study buried pipeline behavior under various loading conditions (Bilgin and Stewart, 2012).

While soil–pipe behavior under monotonic loading is relatively well established, the response of soil–pipe interfaces under seismic conditions remains less understood. Seismic shaking may alter soil density, particle contact, and confinement, thereby affecting interface shear resistance. Previous studies have investigated seismic soil–structure interaction and protection strategies for buried pipelines (Gantes and Bouckovalas, 2016), seismically induced ground deformation effects (Rajah, 2019), and combined seismic and topographic influences on pipeline response (Iyasi et al., 2021). However, experimental data directly quantifying the effect of seismic vibrations on soil–pipe interface friction remain limited.

This study investigates the effect of seismic vibrations on soil–pipe interface behavior through small-scale laboratory testing. A custom-built soil box mounted on a shake table was used to simulate ground vibration, and pullout tests were conducted before and after shaking. The objective was to quantify the change in interface shear strength and displacement characteristics due to seismic excitation and to provide insight into the interaction mechanisms under dynamic conditions.

2 EXPERIMENTAL SETUP AND MATERIALS

2.1 Test box and equipment

A small-scale rectangular wooden soil box was designed and constructed for the pullout tests (Figure 1). The box has inside dimensions of 300 mm in width, 380 mm in length, and 250 mm in height. It was securely fixed to a uniaxial shake table capable of producing controlled horizontal sinusoidal and earthquake motions. The 1994 Northridge earthquake ground acceleration motion (Figure 2) was given as the loading input to the shake table for the tests.

Axial loads and displacements were recorded using a load cell and linear variable displacement transducer (LVDT), both connected to a data acquisition system.

2.2 Test pipe

A polyvinyl chloride (PVC) pipe with an outer diameter of 33 mm and length of 380 mm was placed horizontally at a burial depth of 127 mm (from the surface to the pipe crown).

2.3 Soil

The tests were performed using Ottawa sand, characterized by uniform particle size distribution, (SP soil type based on Unified Soil Classifications System) with $D_{50} \approx 0.71$ mm, $C_U \approx 1.21$, $C_C \approx 0.97$, minimum and maximum dry unit weights of approximately 14.6 kN/m^3 and 17.6 kN/m^3, respectively. The soil was tested in two conditions; dry and slightly moist conditions (with 3% moisture content) to examine the influence of moisture on interface shear behavior.

2.4 Compaction conditions

A bedding layer of Ottawa sand with a thickness of approximately 76 mm was first compacted at the bottom of the box to provide uniform support for the pipe. The PVC pipe was then placed horizontally along the box centerline.

After the pipe was positioned, the remaining sand was placed in three layers. Each layer was approximately 127 mm thick. The compaction was applied to each layer according to planned target density. Compaction was performed using a 1.06 kg hammer dropped from a height of 127 mm. Three preparation conditions were used, based on the soil compaction effort:

1. Loose (no compaction): sand poured freely without tamping (only for dry soil conditions).
2. Medium compaction: each layer compacted with 25 blows.
3. High compaction: each layer compacted with 50 blows.

The corresponding average dry unit weights achieved for loose, medium, and high compaction were approximately 15.70 kN/m^3, 16.50 kN/m^3, and 17.17 kN/m^3, respectively (with relative densities of 37%, 63%, and 86%, respectively).

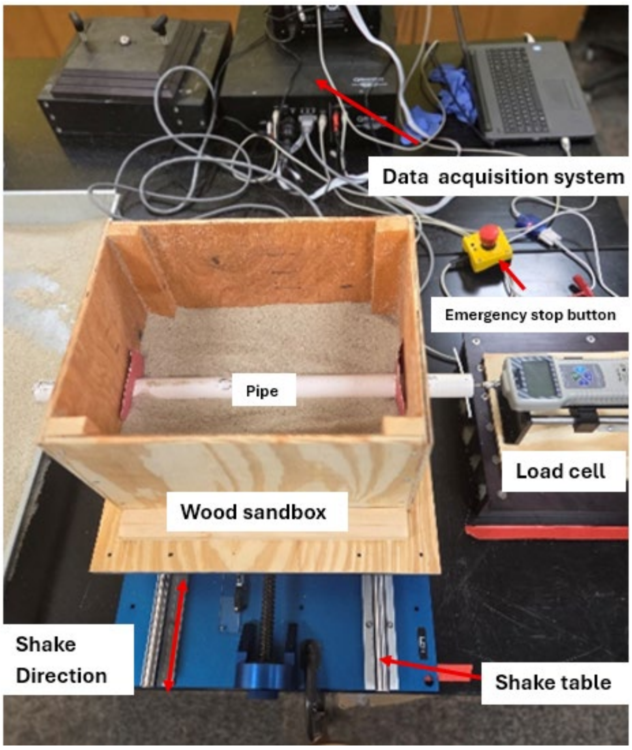

Figure 1. View of the sandbox set up.

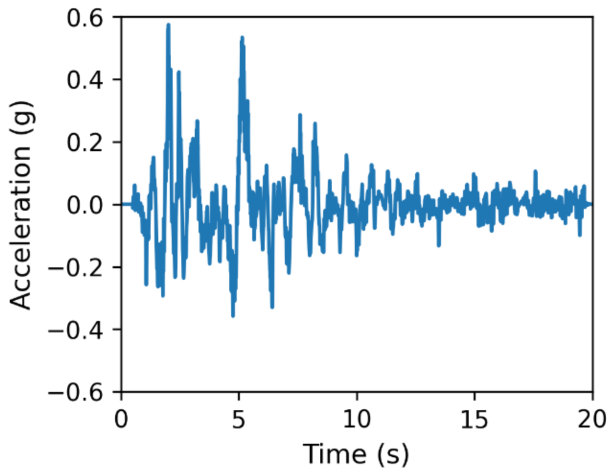

Figure 2. Northridge earthquake ground motion (applied to the shake table).

Each specimen was first subjected to a pre-shaking pullout test. Then the new test setup was prepared with same conditions, and the Northridge-type seismic excitation was applied to the test box. After the earthquake excitation, a post-shaking pullout test was performed.

3 TEST RESULTS AND OBSERVATIONS

3.1 Force–displacement response under different compaction efforts

Figure 3 illustrates the force–displacement behavior of the buried pipe–soil interface under three different soil compaction levels: medium, loose, and dense. All curves exhibit an increase in the interface shear resistance with increasing displacements, followed by a gradual transition toward a nearly constant residual shear resistance. This overall trend represents the mobilization and subsequent stabilization of the interface friction along the pipe–soil contact surface.

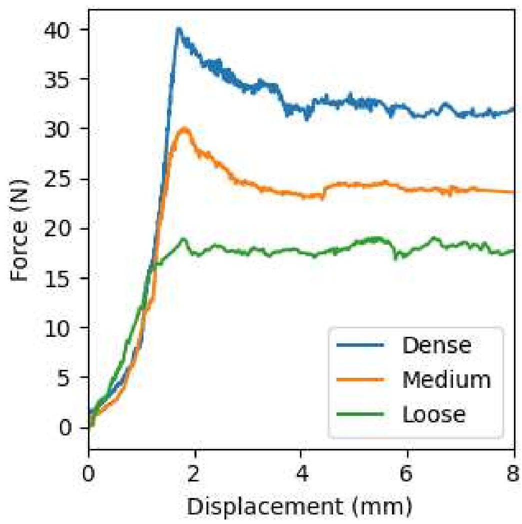

Figure 3. Force–displacement response of pipe–soil interface under different compaction levels (dry soil).

The test with loose soil condition shows the lowest peak resistance, approximately 20 N, due to minimal particle interlocking and reduced confinement around the pipe. As the compaction level increases, both the peak and residual forces increase significantly. The medium-compacted case exhibits a peak resistance of around 33 N. The high-compacted case reaches approximately 40 N peak resistance, with residual strength of about 32 N. These results indicate an interface shear peak resistance increase of nearly 100% from loose to high-compacted conditions, emphasizing the strong dependency of the frictional response on soil density and confinement.

Overall, the experimental results confirm that increasing the degree of soil compaction enhances the interface shear strength ($\tau = \sigma_n \tan \delta$) and normal stress transfer efficiency between the pipeline and the surrounding sand. Achieving at least a medium level of compaction in the pipe's bedding and side fill material can effectively improve the stability and deformation resistance of buried pipelines, while high compaction yields optimal performance for critical infrastructure applications.

3.2 Pre- and post-shaking interface shear strength (dry soil)

Table 1 and Figure 4 present the peak frictional resistance for dry sand under different compaction levels before and after seismic shaking. The initial frictional forces measured were 19.5 N, 32.7 N, and 40.5 N for the loose (no compaction), medium (25 blows), and dense (50 blows) conditions, respectively. After exposure to the Northridge earthquake type ground accelerations and vibrations, the peak frictions increased to 27.9 N, 40.3 N, and 45.5 N, under loose, medium, and dense soil conditions, respectively. This corresponds to friction increases of 54.7%, 23.2%, and 9.6%, respectively. The largest improvement occurred in the loose condition, indicating that shaking promoted densification and enhanced particle interlock at the pipe–soil interface. With increasing compaction, the effect of vibration became smaller because the soil skeleton was already tightly packed and allowed limited rearrangement of particles.

The results demonstrate that seismic vibration can strengthen the soil–pipe interface in dry sand, primarily through vibration-induced densification, with the magnitude of improvement inversely related to the initial density.

3.3 Pre- and post-shaking interface shear strength (moist soil)

Table 2 and Figure 5 present the results of pullout tests conducted in sand containing approximately 3% moisture content under different compaction levels. The peak frictional resistance decreased after seismic shaking for all tested conditions. Before shaking, the measured peak frictions were 27.9 N and 38.9 N for the 25-blow and 50-blow compaction levels, respectively. After shaking, the peak values decreased to 23.6 N and 33.7 N, corresponding to reductions of 15.4% and 13.4%, respectively.

Unlike the dry-soil conditions, where shaking caused densification and increased friction, the moist sand experienced a reduction in the interface shear strength. This can be attributed to the formation of thin water films that lubricated the contact surface between sand particles and the pipe, reducing effective friction. In addition, vibration likely induced local pore-pressure build-up and partial loss of confinement, leading to lower shear resistance.

The loose (no-compaction) condition was excluded from the moisture tests because the combination of high void ratio and low moisture content makes uniform and stable placement difficult. Water tends to migrate downward, leading to non-uniform density and localized soft zones that compromise test repeatability. Therefore, moist tests were limited to the medium (25-blow) and dense (50-blow) compaction levels to ensure consistent density and moisture distribution and reliable evaluation of moisture effects on soil–pipe interface friction.

3.4 Repeatability and data reliability

To verify the reliability of the experimental results, each test was performed twice under identical setup and loading procedures. The peak friction values obtained from the two replicates showed close agreement, confirming very good repeatability of the tests. Table 3 summarizes the replicate results for all soil conditions. The difference between Test #1 and Test #2 values ranged from 0.5% to 10.0%, with an overall average variation of about 5%. Considering the measured relatively small loads, this low percentage difference between the replicate tests indicates very good repeatability and reliability of the test results.

Table 1. Pre- and post-shaking peak friction for different compaction levels (dry soil).

Compaction Level	Initial Friction (N)	Friction after Shaking (N)
Loose	19.5	27.8
Medium	32.7	40.3
Dense	40.5	43.5

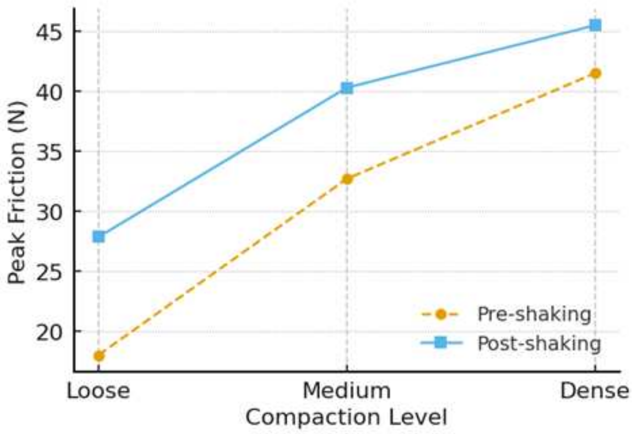

Figure 4. Peak friction versus compaction level under dry soil condition pre and post shaking.

Table 2. Pre- and post-shaking peak friction for different compaction levels (moist soil).

Compaction Level	Initial Friction (N)	Friction after Shaking (N)
Medium	27.9	23.6
High	38.9	33.7

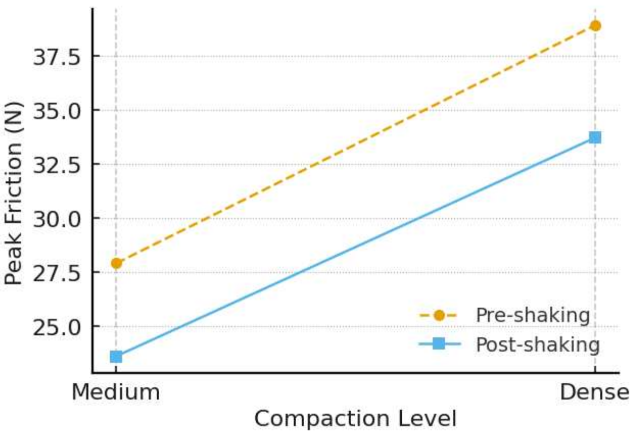

Figure 5. Peak friction versus compaction level under moist soil condition pre- and post-shaking.

Table 3. Replicate test results showing peak friction consistency under different soil conditions.

Soil Conditions (Pre-Shaking)	Test #1 (N)	Test #2 (N)	Difference (%)
Dry Loose	19.5	19.6	0.5
Dry Medium	31.8	33.6	5.7
Dry Dense	41.1	39.9	2.9
Moisture Medium	26.8	29.0	8.2
Moisture Dense	39.4	38.4	2.5
Soil Conditions (Post-Shaking)	**Test #1 (N)**	**Test #2 (N)**	**Difference (%)**
Dry Loose	27.3	28.3	3.7
Dry Medium	39.8	40.8	2.5
Dry Dense	41.9	45.1	7.6
Moisture Medium	22.9	24.3	6.1
Moisture Dense	32.1	35.3	10.0

These results indicate that the experimental procedures, including soil preparation, compaction, and data acquisition, were consistent and well controlled. The small variation between replicates confirms that the measured peak friction forces are reproducible.

4 CONCLUSIONS

This study experimentally examined how seismic loading influences the soil–pipe interface friction using small-scale pullout tests under dry and moist soil conditions. The results show that soil density and moisture content affect the soil-pipe interface shear strength both, irrelevant of ground vibrations.

In dry sand, seismic vibration increased the peak interface friction because of vibration-induced densification and improved contact between the pipe surface and surrounding particles. The increase was most significant in the loose condition, while the effect decreased as the soil density increased, due to the limited particle rearrangement opportunity in denser soil conditions.

In contrast, in moist sand containing approximately 3% water, the peak friction decreased after shaking. The reduction was caused by thin water films and partial pore-pressure effects that reduced inter-particle friction and confinement near the pipe.

Replicate tests confirmed excellent consistency, with about 6% difference, on average, indicating high reliability of the experimental procedure.

Overall, the findings demonstrate that seismic vibration can either strengthen or weaken the soil–pipe interface depending on soil compaction and moisture, providing useful insight for evaluating the seismic performance of buried pipelines. Considering that in most field applications soils around the pipe have some moisture, the soil-pipe interface shear strength most likely would decrease post-shaking in most pipeline systems.

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