Lateral Load Tests on Small-Diameter Piles for Slope Remediation

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ABSTRACT

Slope reinforcement and the use of structural pile elements can be an effective slope remediation alternative when conventional remediation practices (e.g., improved drainage) fail to consider the causal factors leading to slope instability (e.g., strength loss due to weathering). An experimental research program was aimed at developing a rapid, cost-effective, and simple remediation system that can be implemented into slope stabilization practices for relatively shallow (< 5 m) slope failure conditions. The non-proprietary remediation technology consists of small-diameter, grouted micropiles. The research program described in this paper establishes the micropiles as a feasible remediation alternative. Details of the experimental testing and the results from selected measurements are presented in the paper. Lateral load tests on drilled and grouted pile elements of two diameters, in which the piles were installed through a shear box and loaded by uniform lateral translation of soil, advanced our understanding of the soil load transfer to the piles. The pile load test plan included three soil types, and the piles were installed into glacial soils of the experimentation site. Instrumentation of the shear boxes and pile reinforcement indicated the load distributions that developed along the piles and the pile response to the physically-imposed boundary conditions. Results show that piles installed in failing slopes will arrest or slow the rate of slope movement. Furthermore, the soil movement associated with slope failures induces lateral load distributions along stabilizing piles that vary with soil stiffness and strength, pile stiffness and section capacities, and the spacing of piles over the slope.

Key words: laterally loaded piles—slope reinforcement—slope stability

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INTRODUCTION

In situ reinforcement methods for stabilizing cut slopes and embankments have included stone columns, soil nailing, and structural pile elements (e.g., drilled piers, micropiles, recycled plastic pins). The use of structural pile elements can be particularly effective when conventional remediation practices fail to address the causal factors leading to slope instability. Pile elements offer passive resistance to downslope soil movement by transferring the loads developed along the pile to stable soil below the failure surface. The soil load transfer to pile elements is a complex soil-structure interaction problem, and the differences in existing design procedures for pile stabilization suggest that the stabilizing mechanisms are not fully understood.

An experimental research program was aimed at developing a rapid, cost-effective, and simple remediation system that can be implemented into slope stabilization practices for relatively shallow (< 5 m) slope failure conditions. The non-proprietary remediation technology consists of small-diameter, grouted micropiles. Recent investigations (e.g., Loehr and Bowders 2003, White and Thompson 2005) have evaluated the use of slender pile elements for stabilizing slopes. Slope remediation with small-diameter piles may more effectively address the cost, environmental impact, schedule, and construction constraints associated with larger drilled piers or driven pile sections. The research program described in this paper establishes the micropiles as a feasible remediation alternative, especially for slope remediations where overexcavation and improved drainage are not appropriate.

RESEARCH METHODS

To develop design concepts, soil-structure interactions for grouted micropiles subject to lateral soil movement were investigated by conducting full-scale lateral load tests. The load tests were performed in a manner similar to large-scale direct shear tests. The direct shear boxes contained compacted soil with known properties and piles that extended through the shear box into glacial soils of the experimentation site. Piles were installed approximately 1.5 m into the existing ground (2.1 m pile lengths) by bottom feeding the concrete mixture into individual boreholes prepared by solid-stem and hollow-stem augers. The shear boxes were pushed laterally to impose uniform lateral translation of soil, modeling the movement of a unit cell of a sliding soil mass. Figure 1 illustrates the load test setup. Instrumentation of the direct shear boxes, including a 222-kN load cell and three string potentiometer displacement gauges, indicated the load-displacement behavior of reinforced soil. Instrumentation of the pile reinforcement consisted of 10 strain gauges to indicate the loads induced on the piles due to lateral soil movement and the pile response to the loads.

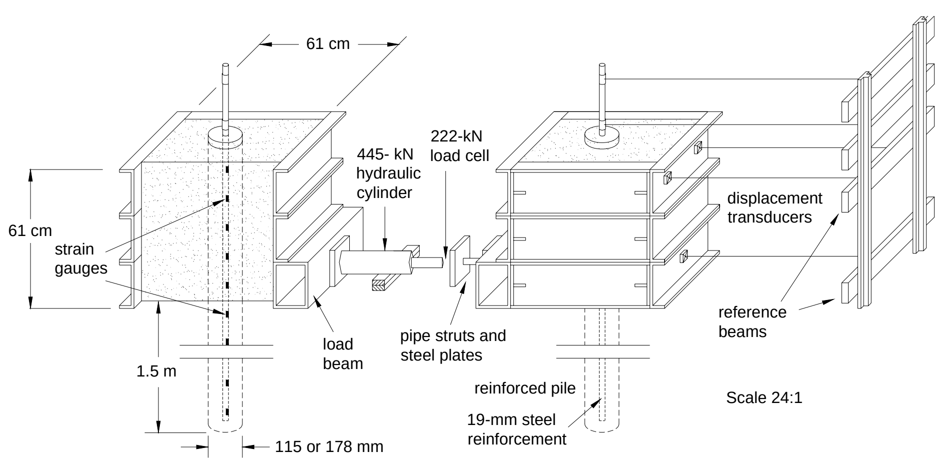

Figure 1. Lateral load test setup

The lateral load test plan evaluated soil type, pile size, and the effect of pile grouping as each parameter relates to the performance of the slope reinforcement system. Each reinforcement parameter influences the response of piles subject to lateral soil movement. The influence of the parameters on pile behavior is evidenced by the dependence of soil load-displacement (p-y) curves on the parameters. The lateral load test plan, provided in Table 1, included 14 different pile configurations. The full-scale load tests were performed to evaluate the performance of 115-mm and 178-mm piles, each reinforced with a centered 19-mm steel rebar.

Table 1. Lateral load test plan

Test Number	Box Number	Box Soil	Pile Size [a]
1	1	Loess	No pile
	2	Weathered shale	No pile
2	3	Glacial till	No pile
	4	Loess	114-mm
3	5	Glacial till	112-mm
	6	Weathered shale	117-mm
4	7	Weathered shale	114-mm [b]
	8	Loess	183-mm
5	9	Glacial till	178-mm
	10	Weathered shale	(2) 113-mm [c]
6	11	Loess	(2) 114-mm [c]
	12	Weathered shale	173-mm
7	13	Glacial till	(2) 113-mm [d]
	14	Glacial till	(2) 115-mm [c]

[a] Measured after pile exhumation
[b] No pile reinforcement
[c] Piles in a row
[d] Staggered piles

Opposing shear boxes were loaded against each other, such that each test involved the simultaneous loading of two boxes. The lateral load tests were performed by monitoring shear box displacement and controlling the load applied to each shear box. Load increments of approximately one kN were applied to the system, and the displacements of each shear box were monitored at the relatively constant load. The next load increment was applied when the rate of displacement for each shear box became small. The loading procedure resulted in test durations ranging from 90 to 180 minutes. The details of pile installation, load test setup, and data acquisition are detailed in White and Thompson (2005) and White et al. (2005).

EXPERIMENTAL TESTING MATERIALS

Soil Properties

The experimental testing was performed at the Iowa State University Spangler Geotechnical Experimentation Site in Ames, Iowa. The site soil profile consists of non-stratified glacial till approximately 1.5 m thick, underlain by sand. The glacial till soil classifies as CL Lean clay with sand; properties of this soil are provided in Table 2.

Table 2. Sampled soil properties

Soil	Classification	Soil property			
		γ_d (kN/m^3)	w (%)	c_u (kPa)*	ε_{50} (%)*
Glacial till (site)	CL Lean clay with sand	13.7	30	35	---
Loess	ML Loess	14.3	30	17	4.5
Glacial till	CL Sandy lean clay	18.9	16	53	2.0
Weathered shale	CL Lean clay	17.4	21	28	1.2

*Undrained shear strength (c_u) and stain at 50 percent of the peak strength (ε_{50}) values based on unconfined compression test results.

As the load test plan evaluated the influence of soil type on pile behavior, three soils (loess, glacial till, weathered shale) from different regions of Iowa were used to fill the shear boxes. The compacted soil from select shear boxes was sampled following the performance of lateral load tests. Soil sampling with thin-walled Shelby tubes and in situ testing devices, namely the dynamic cone penetrometer and K_o stepped blade, helped characterize the soil conditions. Soil properties of the loess, glacial till, and weathered shale are provided in Table 2.

Pile Characteristics

The selection of a concrete mixture design evolved from mixture designs of self-consolidating concrete (SCC) and controlled low-strength material (CLSM). Preliminary mixture proportions and testing results are provided in Table 3. The concrete mixture for the small-diameter piles approximately exhibited the flow properties of CLSM and the mechanical performance properties of SCC. At the test site, slump ranged from 20 to 24 cm, and compressive strengths ranged from 27 to 32 MPa. Compressive strengths were determined by performing compression tests on 76-mm test cylinders from each batch (one batch per pile). The concrete maturity curve from samples prepared in the laboratory and pile concrete strengths from field samples are provided in Figure 2.

Table 3. Preliminary concrete mixture proportions and testing results

Category	Criteria	SCC [a]	CLSM [b]	Selected mixture
Constituent	Cement (lb/cy)	600	100	600
	Fly ash (lb/cy)	n/a	400	125
	Fine aggregate (lb/cy)	1340	2600	2700
	Coarse aggregate (lb/cy)	1700	n/a	n/a
	w/cm	0.55	1.12	0.65
Admixtures	HRWR [c] (fl oz/cwt)	8	n/a	8
	VMA [d] (fl oz/cwt)	2	n/a	2
Performance	21-day strength (MPa)	54.35	2.68	30.34
	Slump (cm)	17.8	27.9	27.4

[a] Schlagbaum (2002)
[b] Center for Transportation Research and Education (2003)
[c] High range water reducer
[d] Viscosity modifying admixture

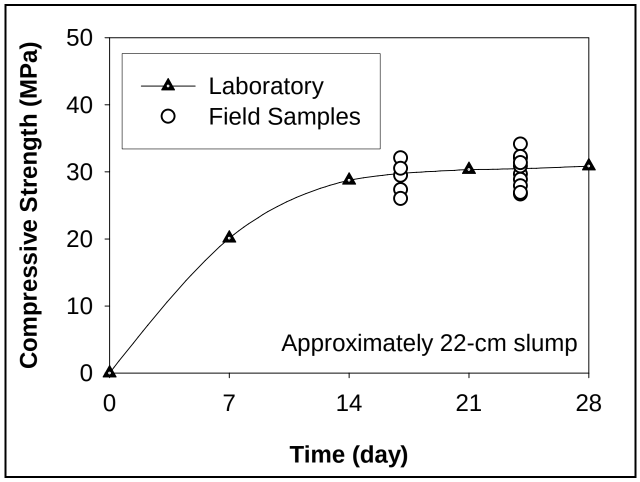

Figure 2. Grout maturity curve and pile compressive strengths

The tensile strength of reinforcing steel was determined by performing a tension test with a 19-mm steel rebar. The stress-strain data provided a yield strength of 455 MPa at $2.8x10^3$ microstrains and a maximum stress of 759 MPa at $8.8x10^4$ microstrains.

LOAD TEST RESULTS

Load Displacement

The measured load-displacement relationships of the shear boxes are provided in Figure 3. The load-displacement relationships for reinforced soil indicate the contribution of the pile to the shear strength of the system, assuming that the difference in load between reinforced shear boxes and unreinforced shear boxes, for a given soil type and lateral displacement, is that load carried by the pile elements. The load-pile head deflection relationships, for brevity not presented here, generally follow those for shear boxes. Pile head deflections were measured to aid the lateral load test analyses.

The 115-mm piles offered considerable resistance to lateral soil movement. The installation of small-diameter piles generally resulted in peak loads ranging from 215% to 325% of the loads for unreinforced soil. The use of 178-mm piles offered additional resistance, with peak loads ranging from 325% to 390% of the loads for unreinforced soil. The installation of two piles offered less resistance than twice that of isolated piles. The peak loads of tests with grouped piles ranged only from 120% to 205% of the loads for tests with isolated piles.

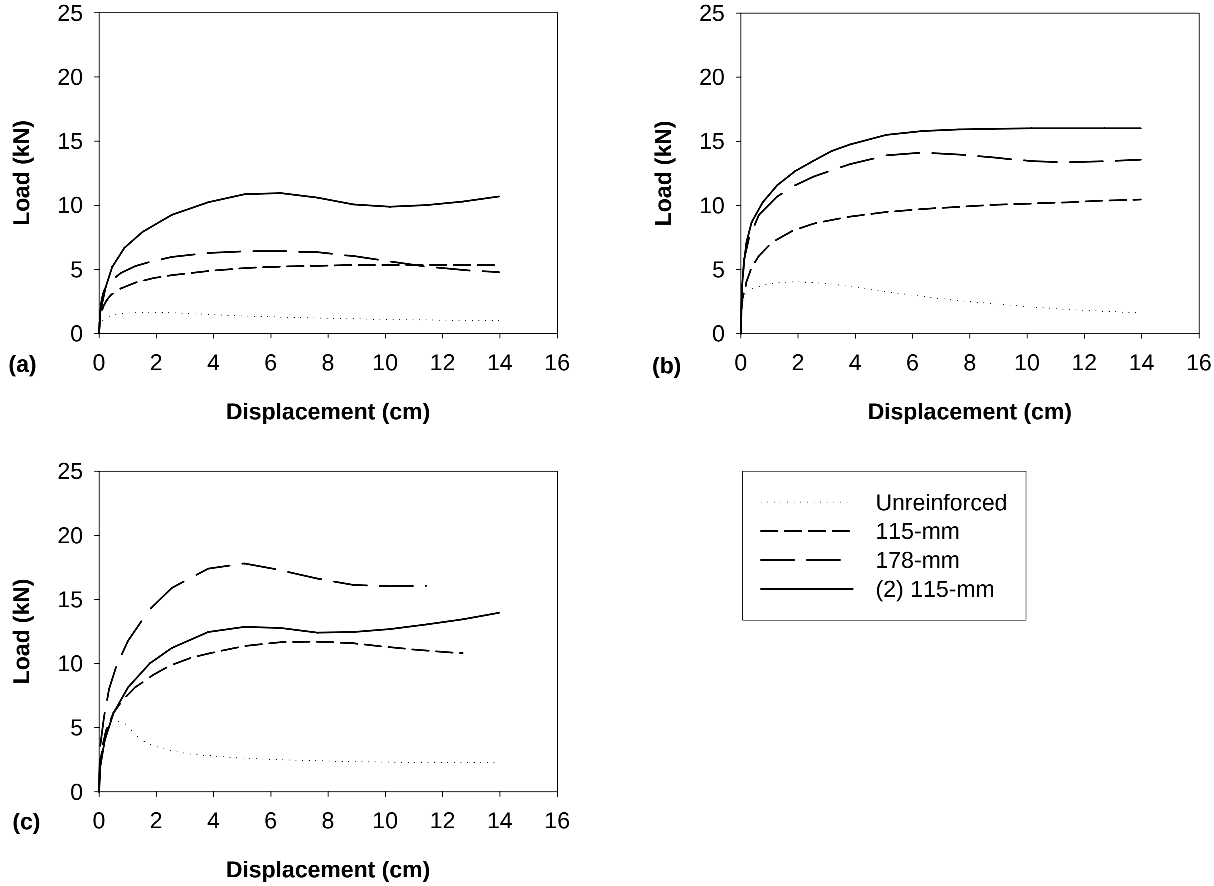

Figure 3. Load-displacement relationships

(a) Loess; (b) glacial till; (c) weathered shale

Behavioral Stages

Graphs of the relative displacement of the shear boxes and pile heads are used to support the observed pile behaviors during the performance of the load tests. During loading, a gap formed in front (i.e., load side) of the pile at the soil surface. Figure 4 relates gap width and load for each test. This figure, in addition to displaying the test data, indicates the behavioral stages of piles subject to lateral soil movement, as follows: Stage 1, mobilization of soil shear stresses and elastic bending of pile; Stage 2, mobilization of pile flexural stiffness; and Stage 3, incipient failure due to mobilization of pile moment capacity. Stage 1 is characterized by relatively linear behavior of the soil and the intact pile element. The stress development at the soil-pile interface is insufficient to cause yielding of the soil or cracking of the pile, such that a gap of negligible width forms. Stage 2 commences with the development of a bending moment in the pile element that causes the tension-carrying concrete to crack. The pile stiffness immediately drops, and the pile element becomes more flexible. Further loading of the pile causes more rapid pile rotation and pile head deflection. Coincidentally, the gap formation occurs more rapidly. Stage 3 commences with the mobilization of the pile moment capacity. Gap formation that occurs during Stage 3 occurs under constant load. The failed pile element is incapable of carrying additional load. Gaps of significant width (approximately 10 mm) form with the mobilization of pile moment capacity.

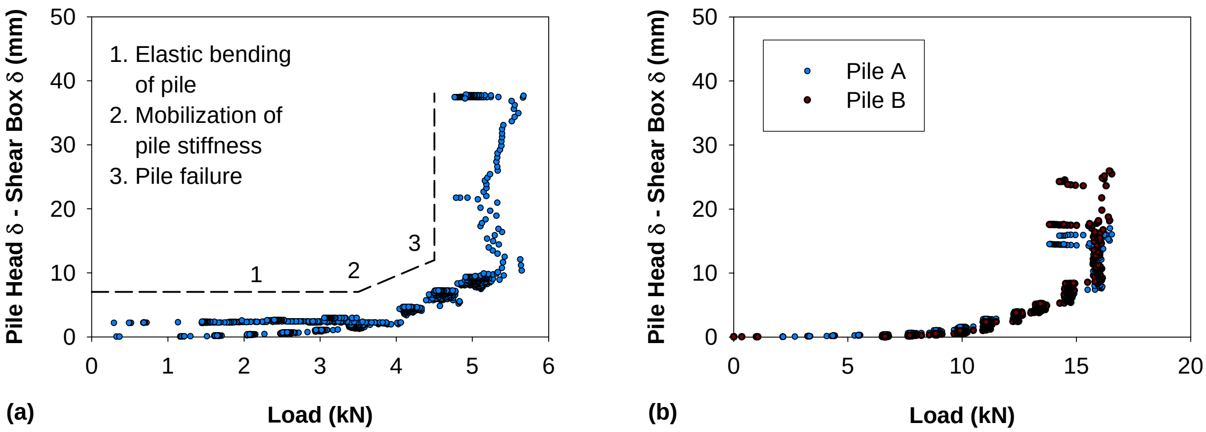

Figure 4. Behavioral stages of piles subject to lateral soil movement

(a) Pile 4; (b) Piles 13A and 13B

Cameras were mounted above the piles of each load test to document the observed behavior of pile heads and surface soil at different stages during pile loading. The pictures, some of which are provided in Figure 5, show the data used to indicate the behavioral stages of piles subject to lateral soil movement. Figures 5 (a) through (c) show the gap formation corresponding to Figure 4 (a), while Figures 5 (d) through (f) show the gap formation corresponding to Figure 4 (b). The pictures also indicate soil stress buildup around the piles. Cracking observed in the surface soil suggests decreasing tangential stresses around isolated piles and soil arching between grouped piles.

Gap formation occurs because the deflection of the pile head, due to rotation of the pile, exceeds the displacement of the surface soil. Pile head deflection exceeded soil movement, even at early stages of the test (see Figures 4 and 5). Poulos (1995) recognized that pile head movement that exceeds soil movement is associated with the intermediate mode, defined by mobilization of soil strength along the pile in both the moving and stable soil. The development of a gap was fundamentally important, because the load distributions along the piles were directly affected by the exposed—and, therefore, unloaded—length of the pile. The length of the pile in which lateral deflection exceeded shear box displacement was more accurately subject to passive soil pressures in the direction opposite that of soil movement.

The K_o stepped blade test (Figure 6 (a)) was incorporated into the soil sampling plan to support the observed soil behavior, specifically the formation of a gap at the soil surface in front of the pile. Associated with the gaps (Figure 6 (b)) are unloaded lengths of pile in the direction of shear box movement and lower lateral soil pressures in front of the pile. Conversely, bulging of the soil was observed behind the pile (Figure 6 (c)). Associated with the bulging soil are lengths of pile loaded in the direction opposing shear box movement and higher lateral soil pressure behind the pile. At greater depths, the lateral soil pressure in front of the pile exceeds the lateral soil pressure behind the pile, confirming that the net load applied to the piles is, in fact, in the direction of soil movement. The interpretation of load development along piles subject to lateral soil movement is support by the K_o stepped blade test results, provided in Figure 7.

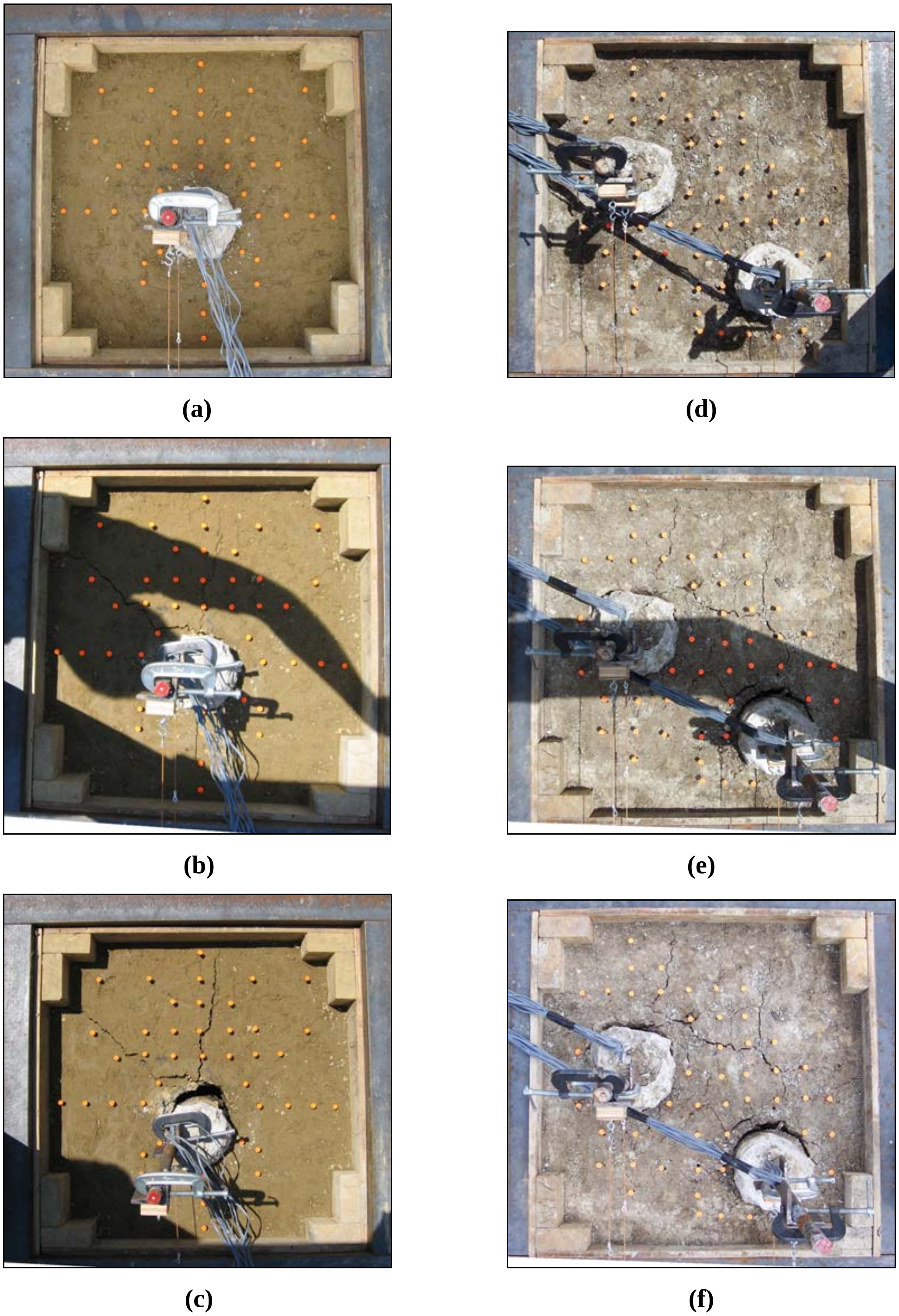

Figure 5. Pile 4 (a, b, c) and Pile 13 (d, e, f) photogrammetry pictures
(a) 0 cm; (b) 5 cm; (c) 16 cm; (d) 0 cm; (e) 10 cm; (f) 14 cm

(a)

(b)

(c)

Figure 6. Load development along piles subject to lateral soil movement

(a) K_o stepped blade test; (b) gap in front of pile; (c) bulging behind pile

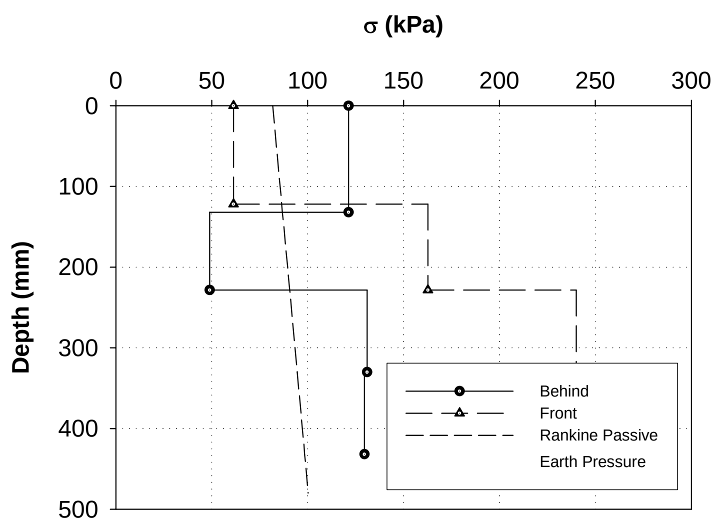

Figure 7. K_o stepped blade test results, load development along piles

Bending Moment

As the evaluation of pile response to loading is generally completed by examining the deflection, shear, and bending moment of a pile, the analysis of test data required an understanding of the relationship between steel strain and bending moment. Data interpretation (i.e., conversion of strain to bending moment) was achieved by performing moment-curvature analyses for the pile sections, with the analysis input parameters being cross-sectional configuration and material properties. For the full range of loading, from an unloaded condition to section failure, the moment-curvature relationship examines member ductility, development of plastic hinges, and redistribution of elastic moments that occur in reinforced concrete sections (Nilson 1997). The analysis additionally provides the strain distribution through pile sections, such that the measured strain of the pile reinforcement is directly related to bending moment. The relationship between pile flexural stiffness (EI) and bending moment is shown in Figure 8 to indicate the stages of pile behavior for the range of possible loading conditions. The relationship between gauge strain and bending moment is included to demonstrate the conversion of measured strain values to bending moments.

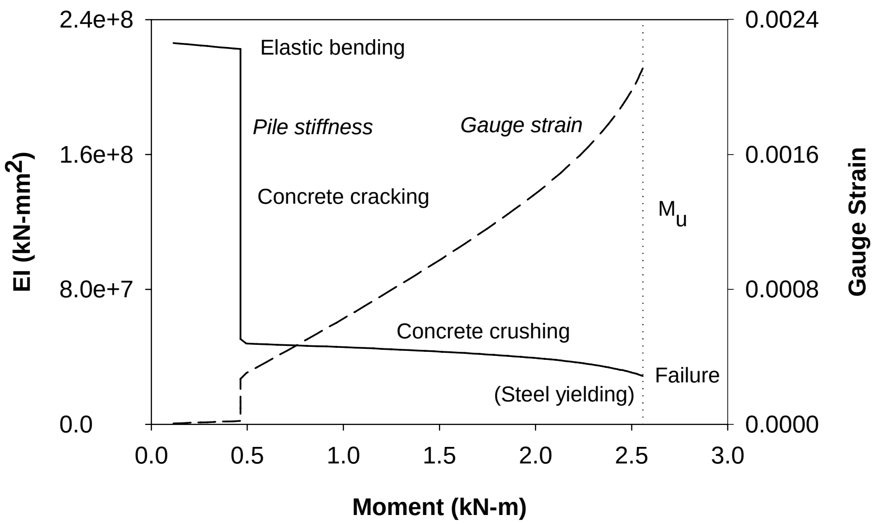

Figure 8. Flexural stiffness gauge strain-bending moment relationship

The strain of steel reinforcement was measured along the entire length of the piles during the lateral load tests. Sample strain profiles for two piles in loess at various loads are provided in Figure 9. All strain profiles provide convincing evidence that piles failed due to mobilization of bending moment capacity and support our interpretation of the behavioral stages of piles subject to lateral soil movement. The maximum measured strain for most isolated piles approximately equaled the strain corresponding to the moment capacity of the pile section. Approximately one-third of the grouped piles mobilized the full bending moment capacity. For tests with grouped piles, the loading system was particularly unstable. The moment capacity was not achieved because these tests were terminated prematurely.

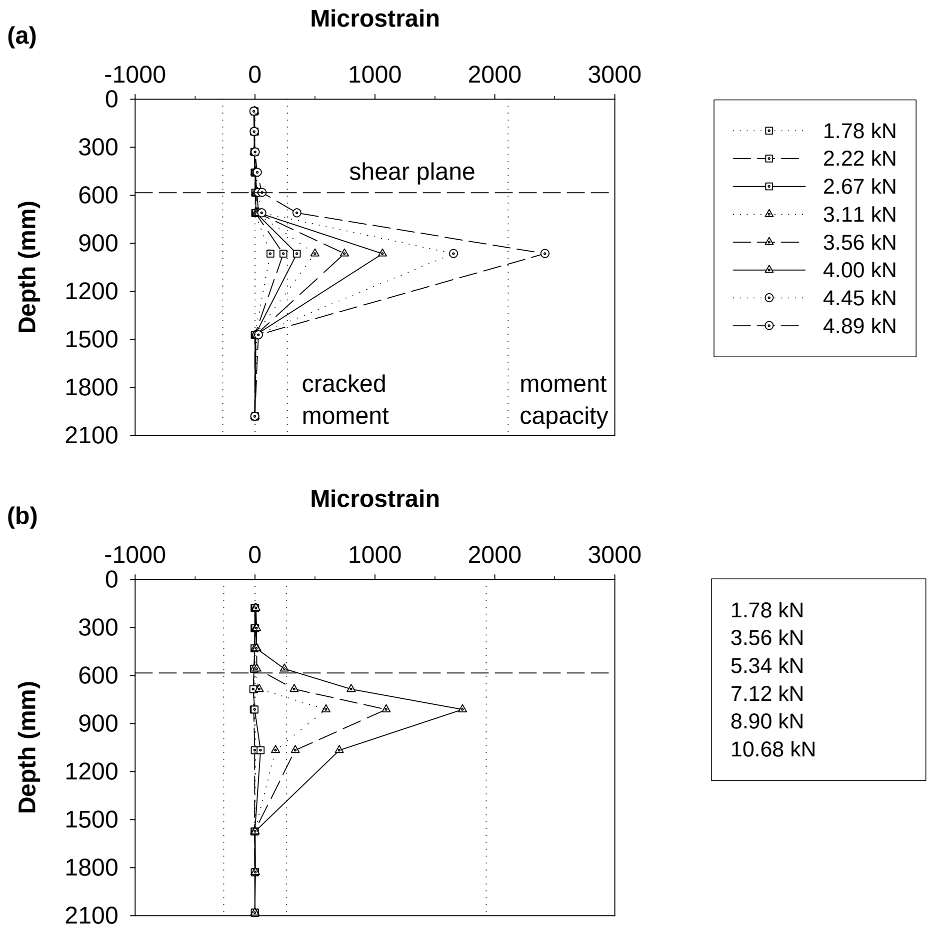

Figure 9. Strain profiles for piles in loess

(a) Pile 4; (b) Pile 11A

SUMMARY

Lateral load tests performed on small-diameter, drilled, and grouted piles indicated that slender pile elements may offer considerable resistance to the soil movement as it occurs during slope failure. The experimental testing is summarized as follows:

1. The pile concrete mixture was developed to exhibit the flow properties of CLSM and mechanical properties of SCC, as slump ranged from 20 to 24 cm and compressive strengths ranged from 27 to 32 MPa.
2. The smaller diameter (115-mm) piles offered considerable resistance to lateral soil movement, with peak loads ranging from 2.15 to 3.25 times those for unreinforced soil. The larger diameter (178-mm) piles offered additional resistance, with peak loads ranging from 3.25 to 3.90 times those of unreinforced soil.
3. Pictures taken from above the shear boxes at different stages of loading indicate stress buildup around isolated piles and the soil arching mechanism that occurs between grouped piles. Nevertheless, the peak loads from load-displacement relationships for tests performed with grouped piles ranged only from 120% to 205% of the loads for tests with isolated piles.

4. The relative displacement of shear boxes and pile heads indicate that behavioral stages of piles are subject to lateral soil movement, recognizing that pile head movement that exceeds soil movement is associated with the intermediate mode.
5. Strain measurements of pile reinforcement provide evidence of pile failure due to mobilization of bending moment capacity. The maximum measured strain for many piles approximately equaled the strain corresponding to the moment capacity of the pile section, based on moment-curvature analyses.

RECOMMENDATIONS FOR IMPLEMENTATION

The research study established small-diameter pile elements as a feasible slope stabilization alternative. Immediate recommendations for future research include the construction and monitoring of pilot projects. Implementation of slope reinforcement through pilot studies, which will help us more fully understand and verify the load transfer mechanisms of the stabilization system, is the next most important task for improving the slope remediation alternative. The outcomes of instrumented pilot projects may include the revision of existing design procedures and increased cost efficiency for use of the method by local transportation agencies. Future research may also include supplementary experimental testing to address the influences of pile orientation and truncation, and advanced numerical studies (e.g., finite element) to address the influences of interactions between adjacent piles.

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