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Development of Expanded Steel Pipe Pile to Enhance Bearing Capacity

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Abstract: An expanded steel pipe pile increases the cross-sectional area of conventional micropile by expanding the steel pipe to exhibit a higher bearing capacity owing to increased frictional resistance. However, construction cases of the expanded steel pipe pile are insufficient due to the absence of equipment for expanding steel pipes inside the ground. In this study, hydraulic expansion equipment was developed to verify the reinforcing impact on the bearing capacity and field applicability of the expanded steel pipe pile. A series of laboratory and test bed experiments was conducted to measure the expansion time and deformation of carbon steel pipes by using the developed equipment. The results of these experiments demonstrated that the developed equipment has sufficient ability and constructability to be used in the field for constructing expanded steel pipe piles. Then, field load tests were performed by constructing expanded and conventional steel pipe piles to confirm the improved bearing capacity of the expanded steel pipe pile compared to that of the conventional micropile. As a result, the expanded steel pipe pile exhibited a 20.88% increase in bearing capacity compared to that of the conventional steel pipe pile.

Keywords: micropile; steel pipe pile; expanded steel pipe pile; bearing capacity of micropile; expansion equipment for steel pipe

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1. Introduction

Underground space development for urban regeneration and sustainability in metropolitan areas has been a focus area for researchers in recent years [1]. Underground space development is the most efficient method to achieve urban regeneration through efficient land use and reduced traffic congestion [2]. However, underground spaces have not been adequately developed in traditional metropolises owing to aging buildings [3]. Old buildings are typically demolished when developing underground space owing to safety concerns. Moreover, pile foundations under superstructures need to be removed during underground space development. A pile foundation is used to transmit the load of a structure to hard ground or to increase the strength of the ground. In metropolitan areas, large-diameter piles with a diameter of 1 m or more are primarily constructed to support large buildings. Thus, the use of grout materials such as bentonite or concrete increases, which leads to contamination of the ground environment. In addition, ground settlement or permanent deformation of the ground may occur when pile foundations are removed for urban regeneration and sustainability. High demolition costs and construction waste are also becoming serious issues.

The increase in the strength of materials and the development in construction technology have resulted in the use of micropiles composed of small-diameter steel pipes recently. Micropiles are advantageous because of their characteristics, such as flexible pile placement, short construction period, and strong field applicability, owing to the use of light construction equipment [4]. In addition, a small borehole volume minimizes the effect of construction materials on the ground environment [5]. Therefore, micropiles have been widely used when it is difficult to construct, or the ground environment needs to be preserved, such as slope stabilization, landslide prevention, etc. Li et al. investigated the seismic response and dynamic behavior of landslides reinforced with micropiles [6]. Kumar et al. analyzed the effect of micropiles on stabilizing slopes [7]. Liu et al. numerically analyzed the impact of reinforcement using a double-row micropile to prevent landslides [8]. Improvement of seismic stability in sandy soil by installing umbrella-type micropile was also confirmed through numerical analysis [9]. The umbrella-type micropile could reinforce the soft clay ground by restraining the horizontal movement of the ground [10]. In addition, micropiles were used for restoration or ground reinforcement when differential settlement occurred due to sinkholes [11]. The cantilever retaining wall on the cut slope has been reinforced with micropiles, and the behavior of micropiles during earthquakes was studied [12].

Concerning urban regeneration, micropiles can be used to reinforce aging buildings and develop underground spaces without demolishing existing buildings [13]. In particular, a method of developing underground space after stabilizing an existing building by installing necessary support members, such as micropiles, to prevent demolition is called a floating and underground extension method. Various support members can be used in the floating and underground extension method. The applicability of truss structures as supporting members of the superstructure (i.e., existing building) was analyzed [14]. The supporting behavior of the superstructure according to various construction methods was also studied [15]. Among them, using micropiles as support members decreases the space required for installation and the effect on the ground environment. Moreover, by using micropiles, construction costs could be saved as the excavation volume of ground increases [16], and approximately 90% of construction waste could be decreased [17]. The stability provided by micropiles as support members in the floating structure method has been demonstrated through numerous construction and measurement cases. Numerical analysis was performed on the axial stiffness of micro piles during the remodeling of a building, and the degree of stiffness required to increase when deterioration occurred was analyzed [18]. Studies have been conducted on a method to improve the stability of existing buildings by creating a shear key of a waveform in a micropile [19] or sharing the support capacity [20].

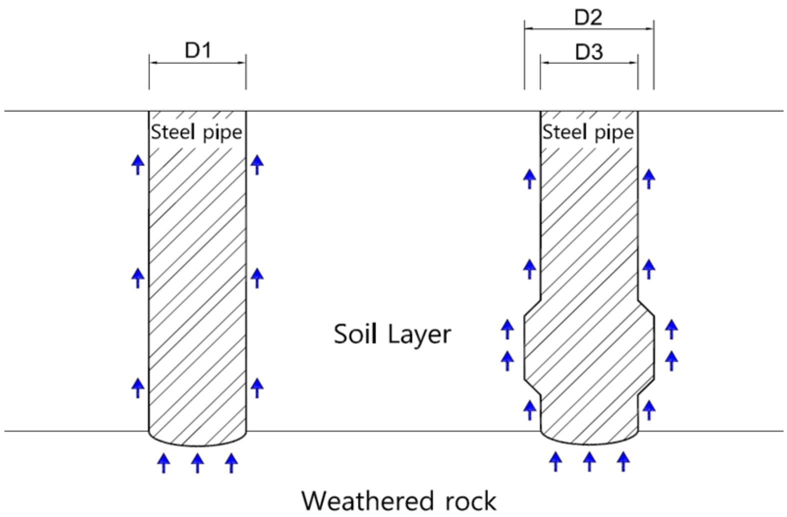
However, micropiles have small cross-sectional areas. Hence, the end bearing capacity does not play a role in supporting the upper structure. In other words, the micropiles are supported exclusively by frictional resistance. Thus, a long micropile is required for supporting high upper structure loads [21]. However, the slender ratio increases corresponding to the increase in micropile length, thereby increasing the risk of buckling. The low resistance to bending of micropiles was evaluated through experiments [4]. In addition, it was confirmed through numerical analysis that as the slender ratio increased, the bending deformation increased [22]. Therefore, in order to increase the resistance to bending, a method of embedding a reinforcing material into a steel pipe [23] or manufacturing an integral vertical pile was studied [9]. However, minimizing the length of a micropile by increasing its frictional resistance is the most effective construction and cost-efficient method for decreasing buckling risk.

Therefore, many studies have recently focused on waveform micropiles that increase the frictional resistance by expanding a part of the main surface by spraying grout under high pressure. Waveform micropiles exhibited 1.4–2.3 times higher bearing capacity than conventional micropiles and a decrease in ground settlement [24]. However, waveform micropiles required expensive equipment for high-pressure grout injection and a large space for operation. In addition, the sprayed grout requires a considerable curing period and can cause contamination, as well as changes in the ground environment. In other words, waveform micropiles negate the benefits of using micropiles as support members, which can be quickly constructed in a narrow space with minimal impact on the ground environment.

Using micropiles with joints is another method to increase the bearing capacity of micropiles. Micropiles with joints are premanufactured and installed after drilling the ground. The bearing capacity of a micropile with joints was 1.6 times greater than that of conventional micropiles [25]. However, since the drilling diameter should be larger than conventional micropile, drilling cost for micropiles with joints increased. In addition, the manufacturing cost of micropile with joints was higher than that of conventional micropiles. Nevertheless, the increase in bearing capacity using a micropile with joints was smaller than that using a waveform micropile. This is because a micropile with joints increased frictional resistance in the shape of the joints, whereas a waveform micropile increased bearing capacity by directly increasing the diameter of piles.

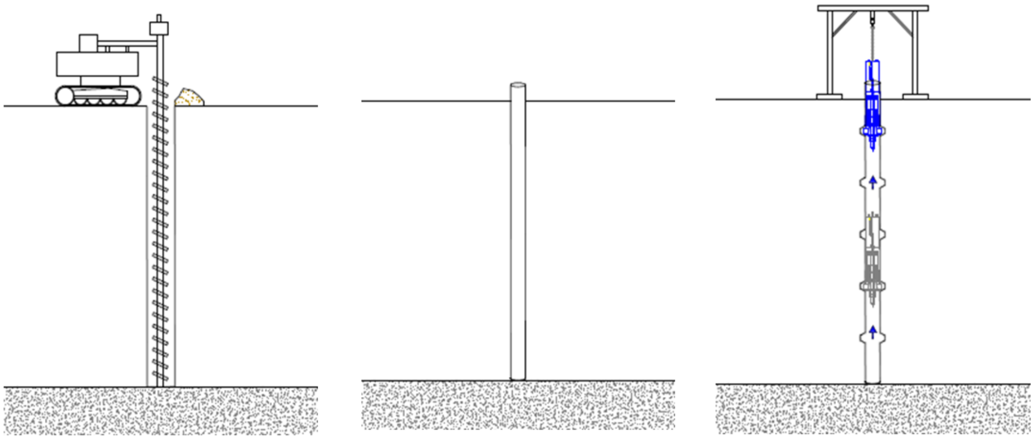
To supplement improved micropiles introduced above (i.e., waveform micropiles and micropiles with joints), an expanded steel pipe pile has been provided as another example of modified micropiles [26]. Figure 1 illustrates the configurations and bearing capacity characteristics of a conventional steel pipe pile and expanded steel pipe pile. The expanded steel pipe pile has 'jaw' (expansion) shapes (i.e., shear keys) by expanding the steel pipe, which increases the end bearing capacity and skin friction force. Contrary to the conventional micropiles where the diameter is constant (D1 in Figure 1), the diameter of the expanded steel pipe pile increases at the jaw shapes (D2 in Figure 1) compared to the diameter before the expansion (D3 in Figure 1). The construction sequence of an expanded steel pipe pile is shown in Figure 2.

Expanded steel pipe piles can be constructed using the same drilling equipment as that used for constructing conventional micropile. Moreover, the steel pipe expansion process is fast and straightforward. This reduces the construction costs and period compared to those required for constructing other improved micropiles. Existing steel pipes can be expanded with expansion equipment for constructing the expanded steel pipe pile, resulting in additional manufacturing cost savings. Above all, since the expanded steel pipe pile directly increases the diameter of the pile, the increase in bearing capacity is also expected to be significant. However, construction cases of the expanded steel pipe pile are insufficient due to the absence of equipment for expanding steel pipes inside the ground.



(**a**) (**b**)

Figure 1. Configuration and bearing capacity characteristics of conventional steel pipe pile and expanded steel pipe pile: (**a**) Conventional steel pipe pile; (**b**) Expanded steel pipe pile.



(**a**) (**b**) (**c**)

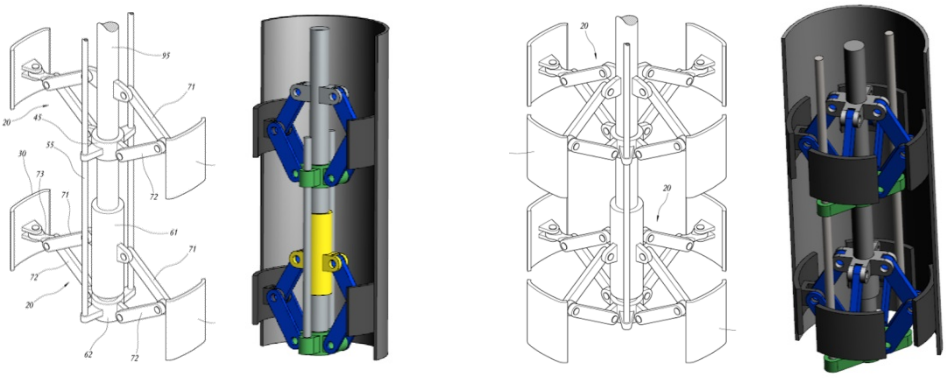
Figure 2. Construction sequence of expanded steel pipe pile: (**a**) Boring; (**b**) Insertion of steel pipe pile; (**c**) Expansion of steel pipe at constant intervals.

In this study, novel steel pipe expansion equipment was developed, and its performance was verified through a series of experiments. First, prototypes of the expansion equipment were manufactured according to the expansion method, and expansion equipment with superior performance was selected. Subsequently, laboratory and test bed experiments were performed to measure the maximum expanded diameter and duration using the selected prototype depending on the thickness of the steel pipe. Optimal expansion equipment was designed and manufactured based on the experimental outcomes. Finally, field load tests were conducted by constructing full-scale conventional and expanded steel pipe piles to compare the bearing capacity of the two piles.

2. Prototype Development of Expansion Equipment

2.1. Mechanical Equipment for Expanding Steel Pipe

The expansion equipment for the steel pipe pile should be inserted inside the steel pipe pile drilled underground to expand the pipe. Therefore, applying even pressure is necessary to form a jaw on the steel pipe. Mechanical, hydraulic, and pneumatic methods can be adapted to expand the steel pipes. First, the mechanical expansion equipment was designed to press the pipe with blades from the central axis and rotate the blades to apply pressure constantly. Two- and four-way types of mechanical expansion equipment were designed based on the operation method of the blades, as shown in Figure 3.



(**a**) (**b**)

Figure 3. Design concept of mechanical expansion equipment for expanding steel pipe according to operation method of blades: (**a**) Two-way type of mechanical expansion equipment; (**b**) Four-way type of mechanical expansion equipment.

The two-way mechanical expansion equipment was insufficient in creating necessary expansions. Hence, a prototype of the four-way mechanical expansion equipment was manufactured using three-dimensional printing technology (Figure 4). Operational and structural problems during expansion were analyzed using the manufactured equipment. As a result, pressurizing inside the steel pipe was difficult because of its complex operating method. In addition, rotating the blades could not expand a steel pipe consistently. Structural damages, such as breaks and stress concentration, also occurred in joints and members repeatedly during the application of pressure.

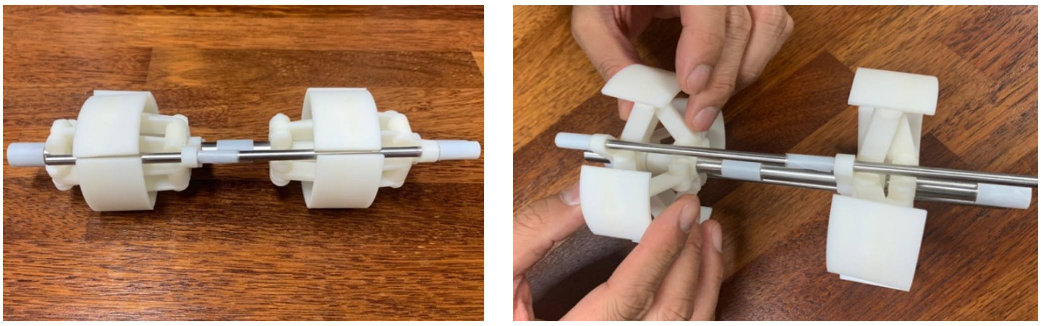


Figure 4. Prototype of four-way type of mechanical expansion equipment.

2.2. Hydraulic Equipment for Expanding Steel Pipe

The hydraulic expansion equipment has a simple structure to expand the steel pipe. Thus, the design and manufacturing processes are straightforward, including few breakdowns and easy repairs. In particular, hydraulic expansion equipment has excellent applicability for underground owing to low noise. A prototype of the hydraulic expansion equipment was manufactured to evaluate its performance and applicability. The prototype has a small diameter of 100 mm. The equipment opens expander A, depicted in Figure 5, by pulling the steel bar that held the steel cone (i.e., expander B shown in Figure 5). Then, expander A expands the surrounding steel pipe to constant pressure. Hydraulic ports (ports A and B in Figure 5) were placed on the rear of the hydraulic expansion equipment to pull the steel bar.

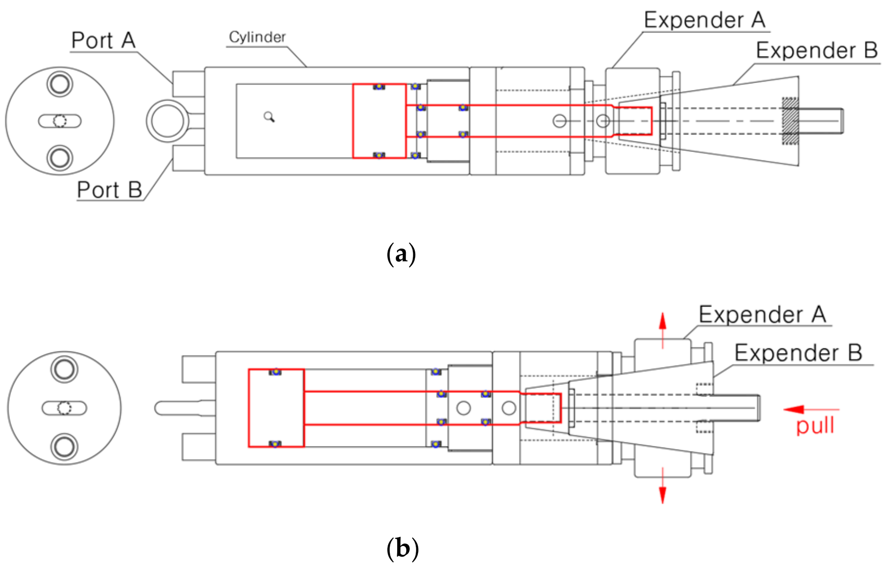
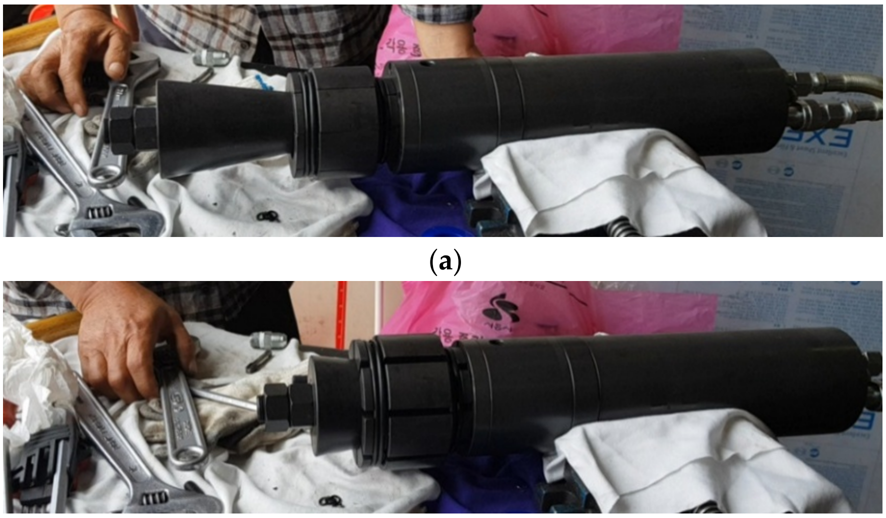


Figure 5. Design of prototype of hydraulic expansion equipment: (**a**) Cross section before expansion of steel pipe; (**b**) Cross section after expansion of steel pipe.

Considering the expansion efficiency of the steel pipe analyzed in the previous study, the hydraulic system was designed to exert the maximum pressure of 70 MPa [26]. In the preliminary experiment, the diameter of the steel pipe was expanded by 20 mm with the prototype of hydraulic expansion equipment. The expanded pipe width was 50 mm, and the expansion angle was maintained below 45°. The prototype of hydraulic expansion equipment is shown in Figure 6.



(a)

(b)

Figure 6. Manufactured prototype of hydraulic expansion equipment: (**a**) Before expansion of steel pipe; (**b**) After expansion of steel pipe.

2.3. Experiment on Prototype of Hydraulic Expansion Equipment

2.3.1. Result of Laboratory Experiment

After inserting the prototype of hydraulic expansion equipment into the steel pipe, the maximum pressure (70 MPa) was applied to measure the expansion time and deformation. Carbon steel pipes were used as specimens, and six experiments were performed using steel pipes with different thicknesses (i.e., 2.9, 4.0, 6.0 mm). The experimental conditions and processes are listed in Table 1 and illustrated in Figure 7, respectively.

Table 1. Laboratory experiment conditions for prototype of hydraulic expansion equipment.

Thickness	Diameter	Length	Expanding Pressure
2.9 mm 4.0 mm 6.0 mm	114.3 mm	1000 mm	70 MPa

The steel pipe specimens after expansion process are shown in Figure 8. The results of the six laboratory experiments for the prototype of hydraulic expansion equipment are summarized in Table 2.

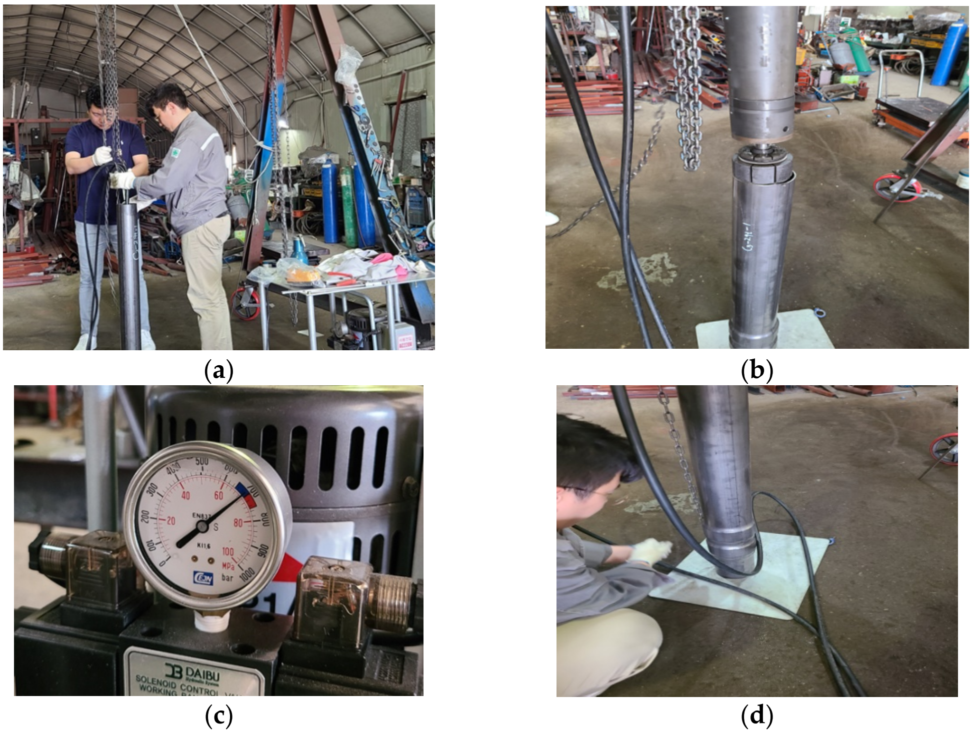


Figure 7. Laboratory experiment process for prototype of hydraulic expansion equipment: (**a**) Insertion of prototype of hydraulic expansion equipment into steel pipe; (**b**) Installation of prototype of hydraulic expansion equipment; (**c**) Application of expanding pressure; (**d**) Steel pipe after expansion process.

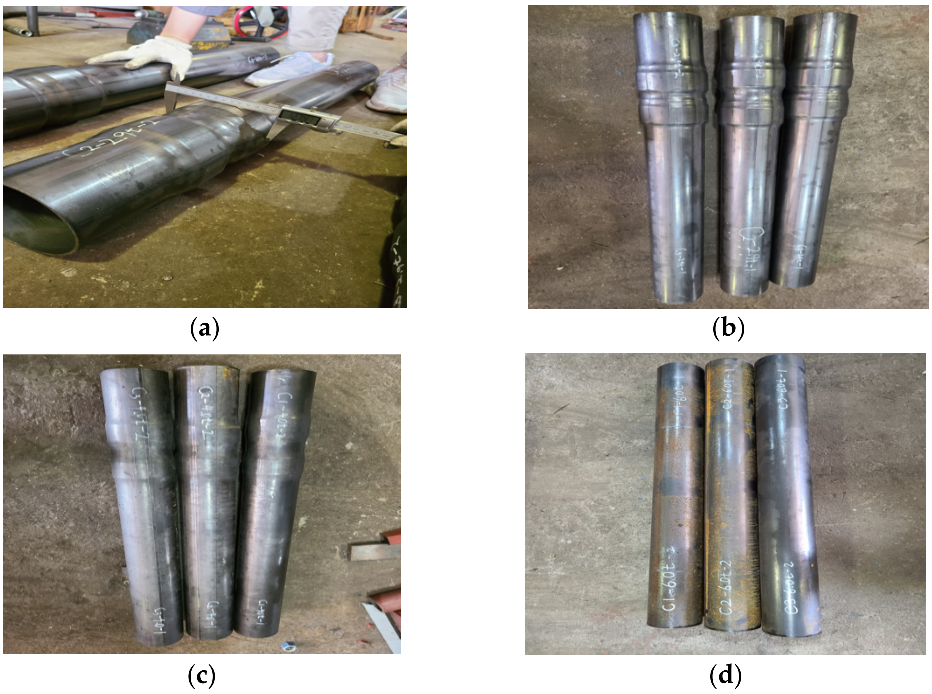


Figure 8. Specimens of steel pipe after expansion process depending on thickness: (**a**) Measurement of expanded steel pipes; (**b**) Steel pipe with 2.9 mm thickness; (**c**) Steel pipe with 4.0 mm thickness; (**d**) Steel pipe with 6.0 mm thickness.

Table 2. Summary of laboratory experiment results for prototype of hydraulic expansion equipment.

Thickness	Measured Data	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
2.9 mm	Deformation (mm)	15.00	13.30	13.75	13.23	14.25	14.32
	Expanded diameter (mm)	129.18	127.48	127.93	127.41	128.43	128.50
	Expansion time (s)	43.13	41.53	41.95	41.32	42.32	42.69
4.0 mm	Deformation (mm)	8.24	8.43	7.67	8.58	7.96	8.31
	Expanded diameter (mm)	122.59	122.78	122.02	122.93	122.31	122.66
	Expansion time (s)	26.26	26.27	25.91	26.35	25.95	26.23
6.0 mm	Deformation (mm)	0.86	0.69	0.67	0.65	0.72	0.82
	Expanded diameter (mm)	115.34	115.17	115.15	115.13	115.20	115.30
	Expansion time (s)	11.00	10.49	10.42	10.18	10.65	10.73

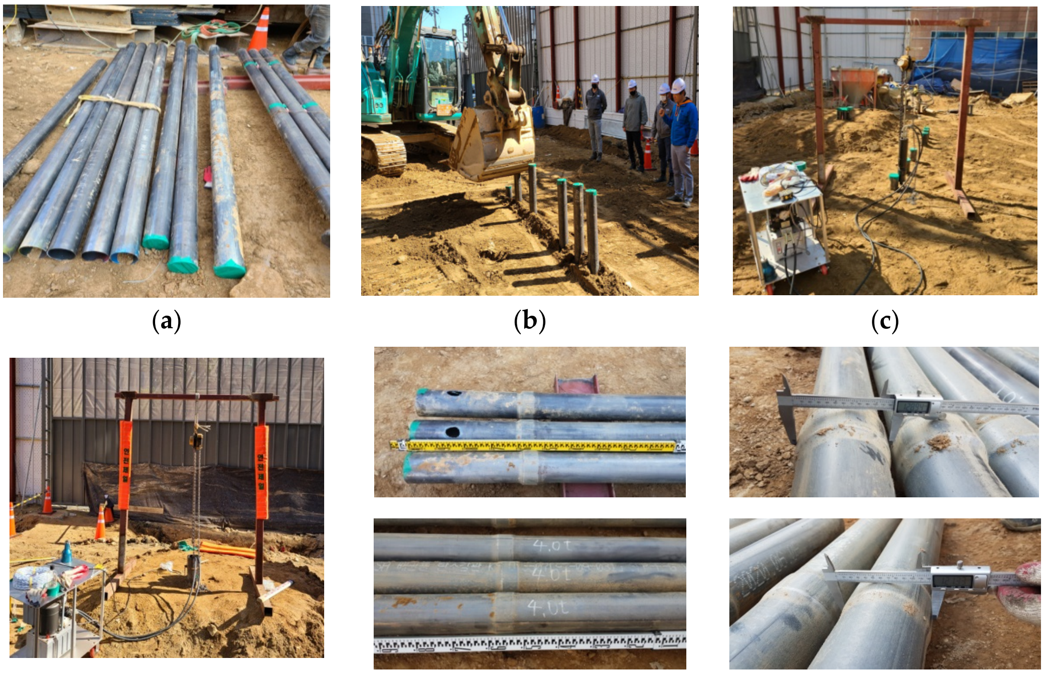
In the previous study, the pipe expansion strain (i.e., deformation) and expansion time were derived as the main factors affecting the bearing capacity and constructability, respectively [26]. In the laboratory experiments, the maximum deformation of the steel pipe with 2.9, 4.0, and 6.0 mm thickness was 15.00, 8.58, and 0.86 mm, respectively. Since the applied maximum pressures were identical in all experiments, the thicker the steel pipe, the less significant deformation occurred. The expansion in a 6.0 mm thick steel pipe was minuscule. In other words, the prototype of hydraulic expansion equipment was not suitable for expanding the steel pipe having a thickness of 6.0 mm. Considering that most of the steel pipes of micropiles used in the field have a thickness of 6.0 mm or more, it was necessary to develop expansion equipment with improved pipe expansion ability. The maximum expansion time for the 2.9, 4.0, and 6.0 mm thick steel pipes was 43.13, 26.35, and 11.00 s, respectively. The maximum pressure was attained rapidly as the steel pipe thickness increased. The deformation in the 4.0 mm thick steel pipe was approximately 41% lower compared to that in the 2.9 mm thick steel pipe owing to increasing thickness. However, the expansion time for the 4.0 mm thick pipe remarkably decreased by approximately 38% compared to that for the 2.9 mm thick steel pipe, ensuring high constructability. Therefore, 4.0 mm thick and 6.0 mm thick steel pipes were buried in the ground, and the expansion ability and time were additionally evaluated.

2.3.2. Result of Test Bed Experiment

Six steel pipes with a length of 3.0 m (three pipes with a thickness of 2.9 mm and the other three with a thickness of 4.0 mm) were drilled into the ground for the test bed experiments on the prototype of hydraulic expansion equipment. Steel pipes with a thickness of 6.0 mm were excluded from the field test because the laboratory experiment demonstrated that the expansion in a 6.0 mm thick steel pipe was minuscule. Subsequently, the prototype of hydraulic expansion equipment was inserted into the steel pipes installed underground and expanded the pipes at depths of 0.5, 1.5, and 2.5 m. The expansion in the pipes induced by the prototype was visually confirmed by digging up the steel pipes using a backhoe. The experimental conditions are listed in Table 3, and the processes of the test bed experiment are illustrated in Figure 9.

Table 3. Test bed experiment conditions for prototype of hydraulic expansion equipment.

Steel Pipe Number	Thickness	Diameter	Length	Expanding Location
3	2.9 mm	114.3 mm	3000 mm	3 depths (0.5, 1.5, 2.5 m)
3	4.0 mm			



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 9. Test bed experiment process for prototype of hydraulic expansion equipment: (**a**) Preparation of steel pipes; (**b**) Insertion of steel pipes into ground; (**c**) Insertion of prototype of hydraulic expansion equipment into steel pipe; (**d**) Expansion of steel pipe using prototype of hydraulic expansion equipment; (**e**) Configuration of expanded steel pipes; (**f**) Measurement of expanded diameter.

The results of the test bed experiment for the prototype of hydraulic expansion equipment are summarized in Table 4.

Table 4. Summary of test bed experiment results for prototype of hydraulic expansion equipment.

Pipe	Thickness	Depth	Expanded Diameter	Deformation	Deformation Rate
1	2.9 mm	0.5 m	128.94 mm	14.64 mm	112.8%
		1.5 m	128.94 mm	14.64 mm	112.8%
		2.5 m	134.09 mm	19.79 mm	117.3%
2	2.9 mm	0.5 m	128.43 mm	14.31 mm	112.5%
		1.5 m	129.16 mm	15.04 mm	113.2%
		2.5 m	124.35 mm	10.23 mm	109.0%
3	2.9 mm	0.5 m	132.98 mm	18.86 mm	116.5%
		1.5 m	133.23 mm	19.11 mm	116.7%
		2.5 m	132.35 mm	18.23 mm	116.0%
4	4.0 mm	0.5 m	121.22 mm	7.04 mm	106.2%
		1.5 m	120.14 mm	5.96 mm	105.2%
		2.5 m	121.48 mm	7.3 mm	106.4%
5	4.0 mm	0.5 m	120.94 mm	6.83 mm	106.0%
		1.5 m	119.94 mm	5.83 mm	105.1%
		2.5 m	120.02 mm	5.91 mm	105.2%
6	4.0 mm	0.5 m	121.37 mm	7.15 mm	106.3%
		1.5 m	119.83 mm	5.61 mm	104.9%
		2.5 m	121.31 mm	7.09 mm	106.2%

The maximum deformations of 19.79 mm and 7.30 mm occurred in the 2.9 mm and 4.0 mm thick steel pipe, respectively. The prototype of hydraulic expansion equipment demonstrated that it could expand the steel pipe even underground. As in the laboratory experiments, the thicker the steel pipe, the smaller the deformation. However, according to numerical analysis in the previous study, the pipe diameter should be at least 1.1 times expanded to have an improved bearing capacity compared to that of the conventional steel pipe pile [26]. The 2.0 mm thick steel pipe expanded 1.1 times or more in diameter, whereas the 4.0 mm thick steel pipe did not. In addition, the deformation in the 4.0 mm thick steel pipe was approximately 59% lower compared to that in the 2.9 mm thick steel pipe, which is more significant than in the laboratory experiments. In other words, the thicker the steel pipe was, the more difficult it was to exhibit the ability to expand the pipe underground when the same pressure was injected. Therefore, full-scale expansion equipment was developed to use a method of controlling the expansion rate rather than maintaining the pressure, and to expand the 6.0 mm or more thick steel pipe.

3. Verification Experiment for Expansion Ability of Full-Scale Expansion Equipment

3.1. Development of Full-Scale Hydraulic Expansion Equipment

Full-scale hydraulic expansion equipment for applying to steel pipes with a diameter of 300 mm or more and a thickness of 6.0 mm or more used in the field was developed (Figure 10). Figure 11 shows the full-scale hydraulic expansion equipment.

(**a**) (**b**)

Figure 10. Comparison of developed hydraulic expansion equipment with its prototype: (**a**) Prototype of hydraulic expansion equipment for steel pipes with diameter of 100 mm; (**b**) Full-scale of hydraulic expansion equipment for steel pipes with diameter of 300 mm or more.

(**a**) (**b**) (**c**)

Figure 11. Manufactured full-scale hydraulic expansion equipment: (**a**) Expander and cylinder; (**b**) Diameter control system; (**c**) Steel pipe expansion device.

The steel pipe was expanded from the inside by hydraulically pulling the steel bar holding the steel cone, identical to that of the prototype expansion equipment. Only, the expansion performance of the full-scale expansion equipment increased significantly, and the expansion rate of steel pipes was controlled, not maintaining the pressure by overcoming the shortcomings of the prototype expansion equipment. A control device was included in the design to adjust the expansion rate of steel pipes automatically.

3.2. Test Bed Experiment for Expansion Ability of Full-Scale Hydraulic Expansion Equipment

A series of test bed experiments was conducted to determine the expansion ability of the manufactured full-scale hydraulic expansion equipment. The steel pipes were expanded in air while adjusting the control device to prevent fracture, as shown in Figure 12. Then, the optimal expansion time and deformation to avoid fracture were measured. A carbon steel pipe with an initial diameter of 318.5 mm, a thickness of 6.4 mm, and length of 1.0 m was used for field testing. A total of 38 experiments were conducted, and the results are summarized in Table 5.

Figure 12. Test bed experiment for expansion ability of full-scale hydraulic expansion equipment: (**a**) Preparation of steel pipe and full-scale hydraulic expansion equipment; (**b**) Expansion of steel pipe; (**c**) Fracture of steel pipe during experiment; (**d**) Steel pipes after experiment.

Table 5. Summary of test bed experiment results for full-scale hydraulic expansion equipment.

Case	Expanded Diameter	Deformation	Fracture	Expansion Time
1	360 mm	41.5 mm		118.21 s
2	360 mm	41.5 mm		117.36 s
3	360 mm	41.5 mm		115.52 s
4	360 mm	41.5 mm		118.21 s
5	359 mm	40.5 mm		120.61 s
6	360 mm	41.5 mm		122.17 s
7	361 mm	42.5 mm		115.32 s
8	362 mm	43.5 mm	fracture	144.43 s
9	362 mm	43.5 mm		115.11 s
10	361 mm	42.5 mm	fracture	141.17 s
11	361 mm	42.5 mm		111.36 s
12	362 mm	43.5 mm		117.59 s
13	361 mm	42.5 mm		113.26 s
14	361 mm	42.5 mm		117.26 s
15	362 mm	43.5 mm	fracture	142.31 s
16	362 mm	43.5 mm	fracture	144.10 s
17	364 mm	45.5 mm		122.09 s
18	360 mm	41.5 mm		122.27 s
19	363 mm	44.5 mm	fracture	150.18 s
20	363 mm	44.5 mm	fracture	152.16 s
21	364 mm	45.5 mm		113.25 s
22	364 mm	45.5 mm		112.41 s
23	364 mm	45.5 mm		115.26 s
24	362 mm	43.5 mm		117.19 s
25	362 mm	43.5 mm		118.45 s
26	364 mm	45.5 mm	fracture	150.21 s
27	364 mm	45.5 mm	fracture	156.31 s
28	364 mm	45.5 mm		122.54 s
29	363 mm	44.5 mm	fracture	155.51 s
30	363 mm	44.5 mm	fracture	150.62 s
31	367 mm	48.5 mm		116.57 s
32	367 mm	48.5 mm	fracture	156.23 s
33	370 mm	51.5 mm	fracture	158.26 s
34	365 mm	46.5 mm	fracture	155.22 s
35	365 mm	46.5 mm		123.47 s
36	367 mm	48.5 mm	fracture	155.51 s
37	367 mm	48.5 mm	fracture	152.21 s
38	370 mm	51.5 mm	fracture	164.11 s

In general, as the expanded diameter of the steel pipe increases, the bearing capacity also increases with the improvement of the jaw effect. However, for the 300 mm diameter steel pipe, the increase rate of the bearing capacity by expanding the steel pipe was insignificant when the steel pipe was expanded to 360 mm or more [26]. Therefore, in this study, the test bed experiment was conducted to expand the diameter to 360 mm or more while adjusting the expansion rate to prevent fracture. In all experimental cases, an expanded diameter of at least 360 mm was secured, and in these cases, the steel pipe expansion was completed within approximately 120 s. When expanding the diameter of steel pipe to more than 360 mm, however, fracture occurred while the expansion time was prolonged. When the fracture occurred, the expanded diameter was in the range of 362 mm to 370 mm, and the expansion time was 141.17 s to 164.11 s. The steel pipes used in the experiments were carbon steel pipes commonly used in the field, and fracture occurred depending on the material performance of the steel pipes. In other words, it is concluded that steel pipes cannot be expanded more than 360 mm without fracture in the field; therefore, the developed full-scale expansion equipment has sufficient ability to be used in the field for constructing expanded steel pipe piles. Moreover, since an expansion of steel pipe could be performed within 2 min, the constructability of the expanded steel pipe piles was remarkable compared to the existing improved micropiles.

3.3. Field Load Test for Field Applicability of Expanded Steel Pipe Pile

Field load tests were performed on the conventional steel pipe pile and expanded steel pipe pile to determine the applicability of expanded steel pipe piles in the field. In other words, the bearing capacities of the two piles were compared with each other. The ground at the field test site consisted of a buried layer of silty sand till a depth of 6.0 m and a weathered soil layer containing silty sand till a depth of 7.5 m. In addition, hard weathered rock and soft rock were distributed below a depth of 7.5 m. A carbon steel pipe having an initial diameter of 318.5 mm and a thickness of 6.4 mm was used for a pile specimen. This was identical to the pipe used in test bed experiment. Only, piles were constructed with a length of 6.0 m. The construction conditions of conventional steel pipe pile and expanded steel pipe pile are shown in Table 6.

Table 6. Field load test conditions for field applicability of expanded steel pile.

No.	Pile	Diameter	Length	Thickness
1	Conventional steel pipe pile	318.5 mm	6000 mm	6.4 mm
2	Expanded steel pipe pile			

Conventional steel pipe pile (No. 1) and expanded steel pipe pile (No. 2) were constructed as per the process shown in Figure 13. Moreover, the field applicability and increase in the bearing capacity of the expanded steel pipe pile were evaluated through field load tests.

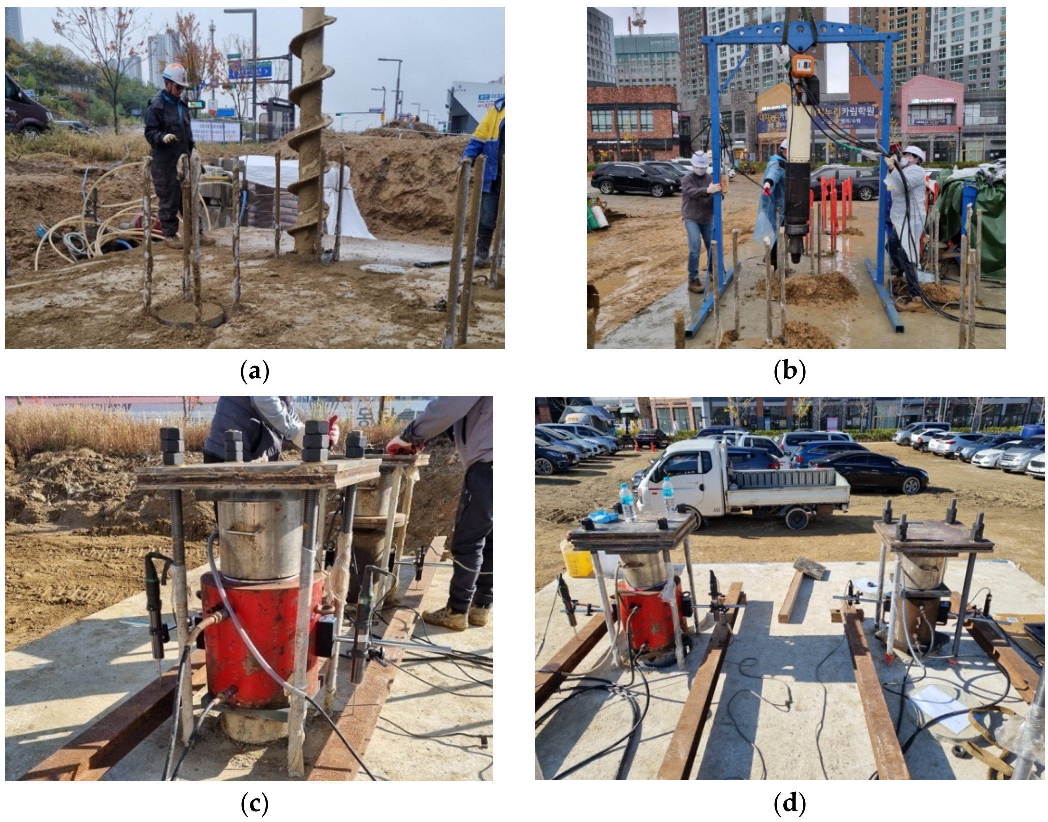


Figure 13. Field load test process for testing field applicability of expanded steel pipe pile: (**a**) Installation of steel pipe; (**b**) Expansion of steel pipe pile using full-scale hydraulic expansion equipment; (**c**) Installation of reaction force devices; (**d**) Static pile load test.

The steel pipe pile was expanded thrice to create three expanded jaws at depths of 4.5 m, 5.0 m, and 6.5 m. The height and diameter of the expanded jaw were 100 mm and 360 mm, respectively. After construction, field load tests were conducted to analyze the load-displacement behaviors of the constructed steel pipe piles. The test was conducted for a load of 49.05 kN at each stage. The results of the field load tests (i.e., load-settlement curve) are plotted in Figure 14.

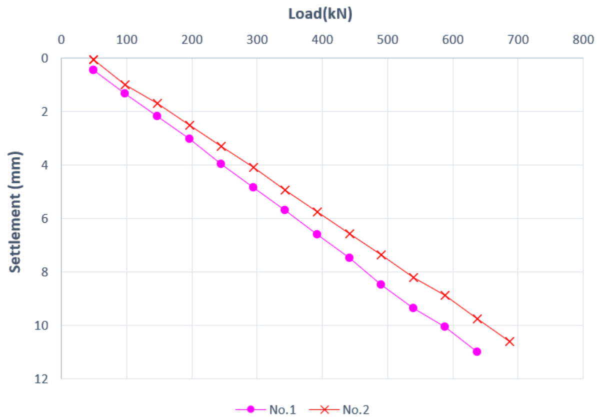


Figure 14. Load-settlement curve based on field load tests.

The load test equipment was set up by estimating the sum of frictional resistance and end bearing capacity to be approximately 300 kN through the statics bearing capacity formula. However, since the ground of the site was harder than expected, the ultimate load could not be confirmed even under a 2-times larger load than the expected bearing capacity (i.e., 300 kN). As a result of measuring up to the limit of the load test equipment, a linear load-settlement curve with no inflection point was obtained. The maximum loads of the conventional and expanded steel pipe piles were 588.6 and 686.7 kN, respectively. The final displacements were 10.99 and 10.59 mm for the conventional and expanded steel pipe piles, respectively. Therefore, the yield load was calculated using the Davisson method and applying a safety factor of 2.0. Then, the allowable bearing capacity of each pile estimated based on yield load was 252.5 and 305.23 kN for the conventional and expanded steel pipe pile, respectively. The bearing capacity of the expanded steel pipe pile increased by 20.88% (approximately 1.2 times) compared to that of the conventional steel pipe pile. The increasing degree was slightly lower than those of other improved micropiles (i.e., waveform micropiles and micropiles with joints). However, the expanded steel pipe pile constructed in this study had a length of 6 m and only three expanded jaws. According to the previous study, the bearing capacity of the expanded steel pipe pile increased exponentially as the number of expanded jaws increased [26]. Therefore, the expanded steel pipe pile has considerable potential in terms of improvement of bearing capacity as the length and number of jaws increase. In addition, as shown in this study, the expanded steel pipe pile has the advantage that the process is very straightforward and economical compared to other improved micropiles.

4. Discussion and Conclusions

In this study, hydraulic equipment was developed for expanding steel pipes in the ground to apply the expanded steel pipe pile to the field. Then, the expansion ability of the developed expansion equipment was confirmed through laboratory and test bed experiments. In addition, an expanded steel pipe pile was installed using the developed expansion equipment, and field load tests were conducted to evaluate the improved bearing capacity compared to the conventional steel pipe pile. The main findings are as follows.

(1) The prototypes of mechanical and hydraulic expansion equipment were produced. The results of the performance test showed that the hydraulic expansion equipment

was suitable for use in the field. However, the prototype of the hydraulic expansion equipment did not sufficiently expand the steel pipe with a thickness of 4.0 mm or more installed underground. Therefore, full-scale expansion equipment was developed to use a method of controlling the expansion rate rather than maintaining the pressure and to expand the 6.0 mm-or-more-thick steel pipe.

(2) The test bed experiment demonstrated that a steel pipe with a thickness of 6.4 mm and a diameter of 318.5 mm could be expanded to a diameter of 360 mm by the developed expansion equipment. Moreover, since an expansion of steel pipe could be performed within 2 min, the constructability of the expanded steel pipe piles was remarkable compared to the existing improved micropiles.

(3) The expanded and conventional steel pipe piles were constructed at the site using the developed hydraulic expansion equipment. Field load tests were conducted to compare the bearing capacities of the two piles after construction. The bearing capacity of the expanded steel pipe pile increased by 20.88% (approximately 1.2 times) compared to that of the conventional steel pipe pile.

The expanded steel pipe pile increased the secondary sectional moment, along with resistance to buckling, by enlarging the cross-sectional area of pipes compared to the conventional steel pipe pile. The increase in the bearing capacity in the expanded steel pipe pile was made by a quick and straightforward process. Moreover, construction costs and the contamination of the ground environment can be decreased because of reduced pile length by increasing the bearing capacity. The amount of demolition and construction waste also can be reduced during underground space development for urban regeneration and sustainability. However, plastic deformation of steel pipes can increase sensitivity to corrosion [27]. In addition, the increasing degree of bearing capacity in the expanded steel pipe pile was slightly lower than those of other improved micropiles. It is expected that this can be complemented by increasing the number of expanded jaws. As such, additional studies are needed for the dissemination of expanded steel pipe piles.

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References

1. Sterling, R.; Admiraal, H.; Bobylev, N.; Parker, H.; Godard, J.P.; Vähäaho, I.; Rogers, C.D.F.; Shi, X.; Hanamura, T. Sustainability issues for underground space in urban areas. *Urban Des. Plan.* **2012**, *165*, 241–254. [CrossRef]
2. Cui, J.; Broere, W.; Lin, D. Underground space utilisation for urban renewal. *Tunn. Undergr. Space Technol.* **2021**, *108*, 103726. [CrossRef]
3. Ministry of Land, Infrastructure, and Transport. A Total of 7,126,526 Buildings Across the Country 3641 Million m^2. Press Release of Department of Green Architecture. Available online: https://www.molit.go.kr/USR/NEWS/m_71/dtl.jsp?lcmspage=1&id=95080363 (accessed on 17 January 2022).
4. Liu, N.; Huang, Y.X.; Wu, B.; Huang, W. Experimental Study on Lateral Bearing Mechanical Characteristics and Damage Numerical Simulation of Micropile. *Adv. Civ. Eng.* **2021**, *2021*, 9927922. [CrossRef]
5. Kim, S.-Y.; Ha, H.-S.; Jo, Y.-B.; Kim, K.-N. Micropiles design and construction. *Mag. J. Korean Soc. Steel Constr.* **2019**, *31*, 37–40.

6. Li, N.; Men, Y.; Yuan, L.; Wang, B.; Li, J.; Liu, X. Seismic response of micropiles-reinforced landslide based on shaking table test. *Geomat. Nat. Hazards Risk* **2019**, *10*, 2030–2050. [CrossRef]
7. Kumar, J.S.; Nusari, M.S.; Purushotam, D.; Prasad, A.I.; Rajyaswori, S. Effectiveness of geocell wall, geogrid and micropile anchors for mitigation of unstable slopes. *Geoenvironmental Disasters* **2021**, *8*, 1–15. [CrossRef]
8. Liu, Z.; Zou, W.; Deng, S.; Fu, Y.; Tang, S.; Gou, D.; Xu, F. A simulation study of the emergency double-row micropile reinforcement of the Xituo Landslide. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *570*, 022039. [CrossRef]
9. Kim, S.-B.; Son, S.W.; Kim, J.M. Horizontal behavior characteristics of umbrella-type micropile applied in sandy soil subjected to seismic motion. *J. Korean Geoenviron. Soc.* **2020**, *21*, 5–16. [CrossRef]
10. Kim, S.-B.; Son, S.W.; Kim, J.M. Horizontal behavior characteristics of umbrella-type micropile applied in soft clay ground subjected to seismic motion. *J. Korea Acad. Ind. Coop. Soc.* **2020**, *21*, 687–695. [CrossRef]
11. Shin, J.G. Study on the Application of Press in Steel Pipe Pile for Restoring Sloped Building by Different Settlement. Master's Thesis, Wonkwang University, Iksan, Korea, October 2020.
12. Sun, Z.; Kong, L.; Wang, Y. Seismic behaviour of a micropile-reinforced cut slope behind a cantilever retaining wall. *Soil Dyn. Earthq. Eng.* **2022**, *152*, 107058. [CrossRef]
13. Kim, S.-B. A Study on Umbrella-Type Micropile Method to Improve Seismic Performance of Existing Facilities. Ph.D. Thesis, Busan National University, Busan, Korea, July 2020.
14. Choi, I.-S. A Study on Applicability Evaluation of Truss Method to Be Applied Underground Downward Extension for Existing Buildings. Master's Thesis, Yonsei University, Seoul, Korea, 2014.
15. Lee, R. Study on The Characteristics and Application of Extension Methods for Underground Space of Existing Buildings. Master's Thesis, Yonsei University, Seoul, Korea, 2012.
16. Seo, S.Y.; Lee, B.; Won, J. Comparative Analysis of Economic Impacts of Sustainable Vertical Extension Methods for Existing Underground Spaces. *Sustainability* **2020**, *12*, 975. [CrossRef]
17. Won, J. Analysis of the Amount of Construction and Demolition Waste Generated by Underground Vertical Extension Methods. In Proceedings of the Korean Institute of Building Construction Conference, Seoul, Korea, 20 May 2021; pp. 273–274.
18. Kim, D.-H.; Jeong, S.-S.; Cho, H.-C. Estimation of the Axial Stiffness of Reinforcing Piles in Vertical Extension Structures. *J. Korean Geotech. Soc.* **2019**, *35*, 35–44. [CrossRef]
19. Wang, C.-C.; Jang, Y.; Kim, S.-J.; Han, J.-T. Numerical analysis of effect of waveform micropile on foundation underpinning during building vertical extension remodeling. *J. Korean Soc. Civ. Eng.* **2019**, *39*, 335–344. [CrossRef]
20. Park, Y.C.; Kim, C.N.; Lee, S.K. Development of Precompression Micropile Which Can Share Load of Existing Foundation. In Proceedings of the Korean Society of Civil Engineers, Pyeongchang, Korea, 17 October 2019; pp. 988–989.
21. Jang, Y.E.; Kim, B.; Wang, C.; Han, J.T. Prediction of vertical bearing capacity of waveform micropile. *Géotechnique Lett.* **2019**, *9*, 198–204. [CrossRef]
22. Kim, T.H. Lateral Bearing Capacity of Triaxial Micropile by Foundation Ground and Installation Angle. Ph.D. Thesis, Chungbuk National University, Cheongju, Korea, July 2021.
23. Li, X.; Bai, M.Z.; Li, T.; Qiu, S.M.; Shi, H. Application of Carbon-Fiber Composite Material in Micropile Structure. *J. Perform. Constr. Facil.* **2020**, *34*, 04020017. [CrossRef]
24. Jang, Y.E.; Han, J.T. Field study on axial bearing capacity and load transfer characteristic of waveform micropile. *Can. Geotech. J.* **2018**, *55*, 653–665. [CrossRef]
25. Jung, C.-W.; Chae, H.-S.; Kim, W.-J. A Study on Vertical Bearing Capacity of Nodular Cylinder Pile. In Proceedings of the Architectural Institute of Korea, Daegu, Korea, 25–28 October 2006; pp. 129–132.
26. Kim, U.; Kim, J.; Kim, J.; Min, B.; Choi, H. Development of Expandable Steel Pipe Piles to Improve Bearing Capacity. *J. Korean Geo-Environ. Soc.* **2021**, *22*, 5–13.
27. Zvirko, O.I. In-Service Degradation of Structural Steels (A Survey). *Mater. Sci.* **2022**, *57*, 319–330. [CrossRef]