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Full Length Research Paper

Pullout resistance characteristics of chain type retaining system

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In this study, we carried out several experiments and implemented three different types of pullout resistive bodies to conduct tests under identical conditions in order to examine the pullout resistance mechanism of chain reinforcement and the resistive elements. Furthermore, pullout resistance characteristics are studied based on laboratory and *in-situ* tests when steel bar and L-type steel angle are used as passive reinforcement. Comparing theoretical and measured values, the measured yield pullout force was 1.2 - 3 times greater than theoretical values depending on the reinforcement method or normal stress. The result indicates that the yield stress is greater for a higher normal stress, a longer chain and when passive reinforcement is combined. The difference was not significant between bar and L-type steel angle in terms of the increase of the yield pullout force.

Key words: Chain-type retaining system, pullout resistance, large scale pullout test.

INTRODUCTION

Soils are relatively strong against compressive external forces, but very weak against tensile stresses. The soil reinforcement system involves installing independent stiffeners at the points where tensile stress acts to reinforce the earth. The application of the soil reinforcement system is on the rise due to very simple construction process and because it maximizes the effectiveness of land development by supplementing the vulnerable material properties of soil and enabling steep slopes and vertical embankments.

Since the frictional resistance at the boundary surface between the backfill soil and reinforcement has to be maximized, sandy soil with a large internal friction angle has been mainly used for a soil reinforcement that retains wall system. Therefore, a major factor that determines the quality of a soil reinforcement wall is that the backfill soil must meet strict quality criteria. However, it has recently become difficult to procure high quality soil and there are demands for simple and economical soil reinforcement systems that can utilize *in-situ* soil (Ingold, 1982; Kim et al., 2002a). Fiber reinforcements, the most widely used type today, can be damaged during the compaction of soil with high percentage of granular soil used (Bergado, 1992). Furthermore, since soil with insufficient friction does not have competent pullout resistance solely with flat-type reinforcements, there are increasing cases where reinforcements with passive resistance are used in conjunction (Abramento and Whittle, 1995; Bacot et al., 1978).

Accordingly, there is a need to develop a system that can maintain the good pullout resistance properties, while minimizing the damage to reinforcements caused by soil compaction. Based on these motivations, a soil reinforcement system using steel chain capable of minimizing damage to reinforcement has been developed. Past studies have focused on the pullout resistance characteristics of the chain used as reinforcement (Inoue and Kominami, 1996; Inoue et al., 1997; PWRC, 1994; Kim et al., 2002a, 2002b, 2003), but it is believed that additional discussion and analyses are required regarding the effects of the chain configuration on pullout resistance characteristics.

In order to isolate and evaluate the elements that constitute chain's pullout resistance – skin friction along

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the chain, shear resistance of the soil inside the chain and passive resistance of the chain - this study implemented three different types of pullout resistive bodies to conduct tests under identical conditions. Based on the results, the study examines the pullout resistance mechanism of chain reinforcement and the resistive elements. Moreover, the surface resistance properties of chain and the changes in pullout resistance characteristics when steel bar and L-type steel angle are used as passive reinforcement are studied based on *in-situ* tests, and the results are compared to propose the characteristics of chain reinforcement.

Pullout resistance mechanism of chain

Reinforcement installed in soil shows different resistance properties against pullout according to the cross-sectional shape, material, installation orientation, installation spacing, effective overburden pressure and soil type (Jones, 1996; McGown et al., 1978). This is because the magnitude of friction between reinforcement surface and soil particles varies according to reinforcement's sectional shape, length and confining pressure (Koivumäki, 1983). Internal stability of a soil reinforcement retaining wall system is examined for two elements. First is the tensile failure of reinforcement related to material properties, and second is failure due to pullout, which can be classified into pullout resistance and bearing or passive resistance according to reinforcement's sectional area and arrangement.

Surface frictional resistance is transferred through the contact surface between reinforcement surface and backfill soil particles, and the level of bond between the two heterogeneous media determines the pullout resistance. The level of bond is generally expressed with friction or bonding coefficient and occurs in a direction parallel to the reinforcement surface.

The magnitude of bond can be easily calculated based on theory. The mechanism of the bearing or passive resistance provided by lateral reinforcement is yet to be fully studied, and experiential values based on experimental results are typically used (Charles and O'Rourke, 1985; Lawson, 1992; Palmeira and Milligan, 1989; Terzaghi et al., 1996).

Pullout resistance of reinforcement can be expressed with a general equation as seen in Equation (1).

$$F_t = F_f + F_b \qquad (1)$$

where $F_f\left(=A_s\sigma_a^{'}\tan\phi\right)$ denotes the frictional resistance between vertically arranged reinforcement and the surrounding soil and $F_b=\left[nwd\left(cN_c+\sigma_v N_q\right)\right]$ the bearing or passive resistance at the front of the displacement progress direction of the vertically arranged reinforcement, indicating the relationship among the cohesion (c) of the backfill material, internal friction angle (ϕ) and the bearing capacity factor in the Terzaghi-Buisman bearing equation (Bergado et al., 1992).

On the other hand, since chain reinforcement has wider surface area and the cross-section varies in repetition, the resistance mechanism is different from that of steel stirrup or geogrid. According to existing literature (Inoue and Kominami, 1996; Inoue et al., 1997), chain's pullout resistance has three major elements: The friction between soil particles and chain (F_1), shear resistance of the soil within chain (F_2) and passive resistance on chain's sectional area (F_3) (Figure 1), which can be written as (Equation 2):

$$F_{tc} = F_1 + F_2 + \mu\cdot F_3 \qquad (2)$$

Where, $F_1 = A_0\cdot 0.5\left(\sigma_v + K_0\sigma_v\right)\cdot\tan\frac{\phi}{2}\cdot n$, $F_2 = 2nA_i\sigma_v\tan\phi$, and $F_3 = n\left(B-D\right)DK_p\sigma_v$.

Equation (2) provides theoretical considerations of every resistive element that can occur in a single chain. In particular, the second term assumes that the soil inside the chain causes shear failure as well as displacement of the reinforcement, the element, which is incorporated as pullout resistance. The third term incorporates the passive resistance that occurs at the front of the progress direction when there is chain displacement as resistance against pullout. However, the actual resistance mechanisms of these terms must be closely examined based on *in-situ* tests.

It has been reported that laterally linking bars between adjacent chains or combining L-type steel angles at chain ends as passive reinforcement increases resistance. Multiple bars can be installed according to the chain length, and pullout resistance with bearing resistance assumption is expressed as shown in Equation (3):

$$F_{ri} = md'\left(cN_c^{'} + \frac{\gamma}{2}d'N_\gamma^{'} + \sigma_v N_q^{'}\right) \qquad (3)$$

The pullout resistance of L-type steel angle with passive resistance assumption is calculated as shown in Equation (4):

$$F_{bi} = K_p\sigma_v A_a \qquad (4)$$

In Equation (3), the bearing capacity factor N_q varies according to the magnitude of lateral reinforcement's displacement and confining pressure. It has been

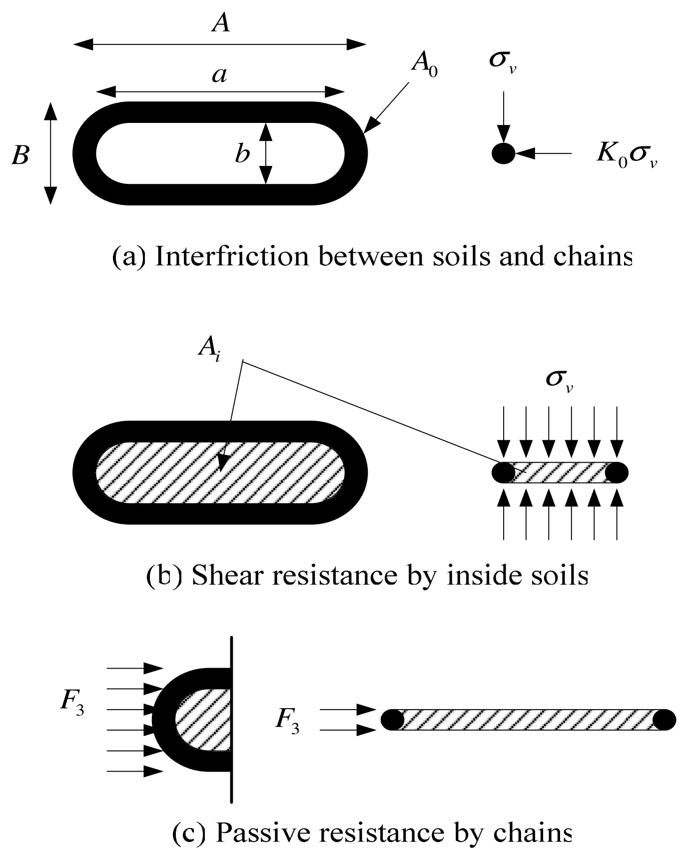

Figure 1. Pullout resistance factors of embedded chain in soils (Inoue et al., 1996).

reported that a low confining pressure causes punching shear failure at the front of reinforcement, a high confining pressure causes general shear failure and a solid ground shows a general shear failure tendency followed by punching shear failure as displacement is increased (Bergado et al., 1992). Accordingly, careful consideration is required for applying the bearing capacity factor based on the state of the ground around reinforcement.

Furthermore, although the resistance of an L-type steel angle is calculated with passive resistance in the equation, Palmeira and Milligan(1989) claimed that lateral reinforcement of an identical shape can display bearing resistance or passive resistance according to the characteristics of the surrounding ground (another point that needs careful attention).

LARGE SCALE PULLOUT TEST

Properties of backfill soil

Mechanical and other laboratory tests were conducted to examine the mechanical and physical properties of the granite soil used in the large-scale pullout test. Figure 2 shows the result of sieve analysis and Table 1 summarizes the results of the laboratory tests conducted to examine soil properties. From Figure 2, the granite soil used in test was estimated as silty sand(SM) in the unified soil classification system.

Experimental conditions for laboratory pullout test

Laboratory pullout test evaluates the friction characteristics between soil and reinforcement for various types of chain reinforcement to ultimately determine the bonding coefficient. The experimental equipment used for the test is depicted in Photo 1 and Figure 3.

A steel model box with dimensions of L127 × W80 × H80 cm was used for the experiment. An air bag was placed on top of the model box so that a constant vertical force could be applied by air pressure. The maximum inflow air pressure was 1.0 MPa, and a steel plate was placed on the top to fix the air bag.

Chain reinforcements of 2.0 - 3.0 m are generally installed *in-situ*. Although it would be ideal to use a chain with a similar length for the laboratory test, an 80 cm

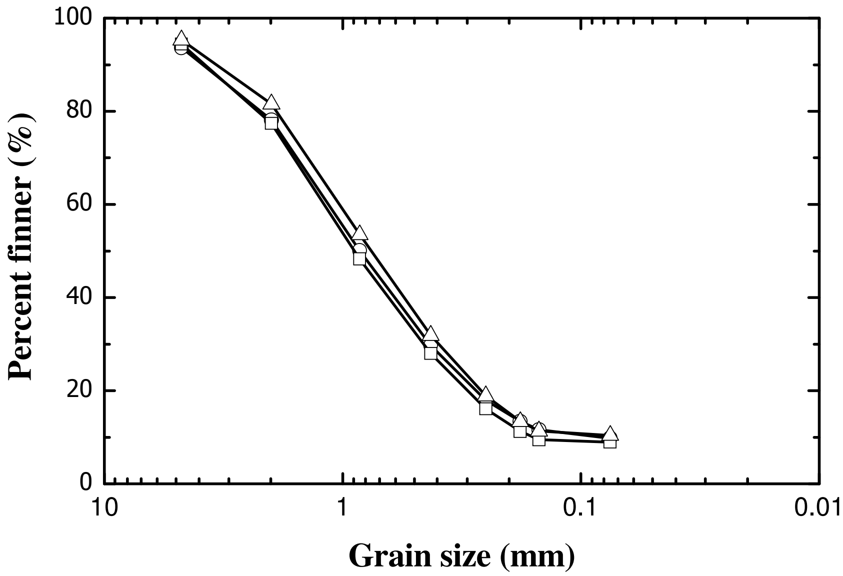

Figure 2. Grain size distribution curve.

Table 1. Physical and mechanical properties of granite soil.

ϕ (deg)	32	k (cm/sec)	9.46×10^{-5}
c (kPa)	14.91	LL (%)	22.44
D_{10} (mm)	0.1~0.15	PL (%)	NP
D_{30} (mm)	0.39 - 0.46	OMC (%)	13.3
D_{60} (mm)	1.0 - 1.2	γ_{dmax} (tf/m^3)	1.85
C_u	8 - 10	D_r (%)	90
C_g	1.15 - 1.17	USCS	SM

ϕ : friction angle; k: hydraulic conductivity*;* c : cohesion; LL: liquid limit*;* D_{10} : effective size; PL: plastic limit; D_{30} : size which 30% of the soil grain particles; *OMC: Optimum moisture content;* D_{60} : size which 60% of the soil grain particles; γ_{dmax} : max. dry unit weight; C_u : coefficient of uniformity ; D_r: relative density; C_g : coefficient of curvature; USCS: unified soil classification system.

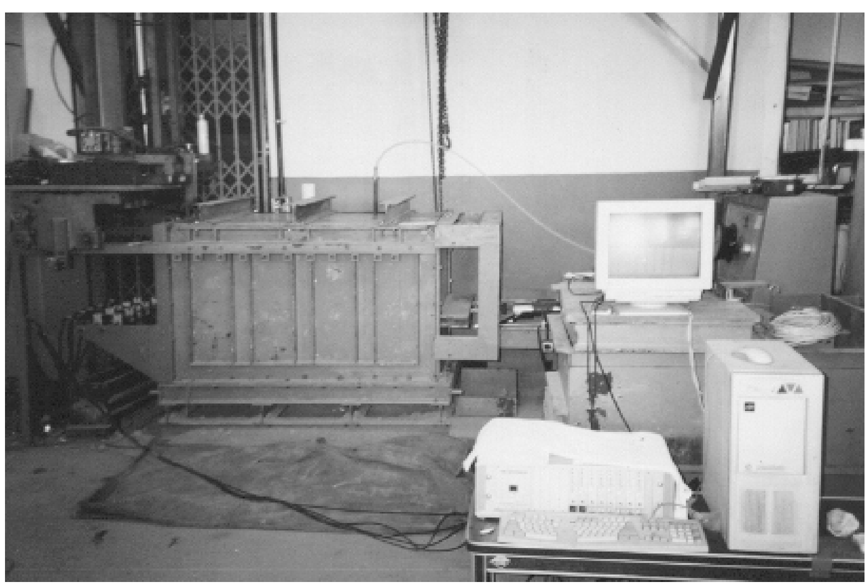

Photo 1. Experimental equipment.

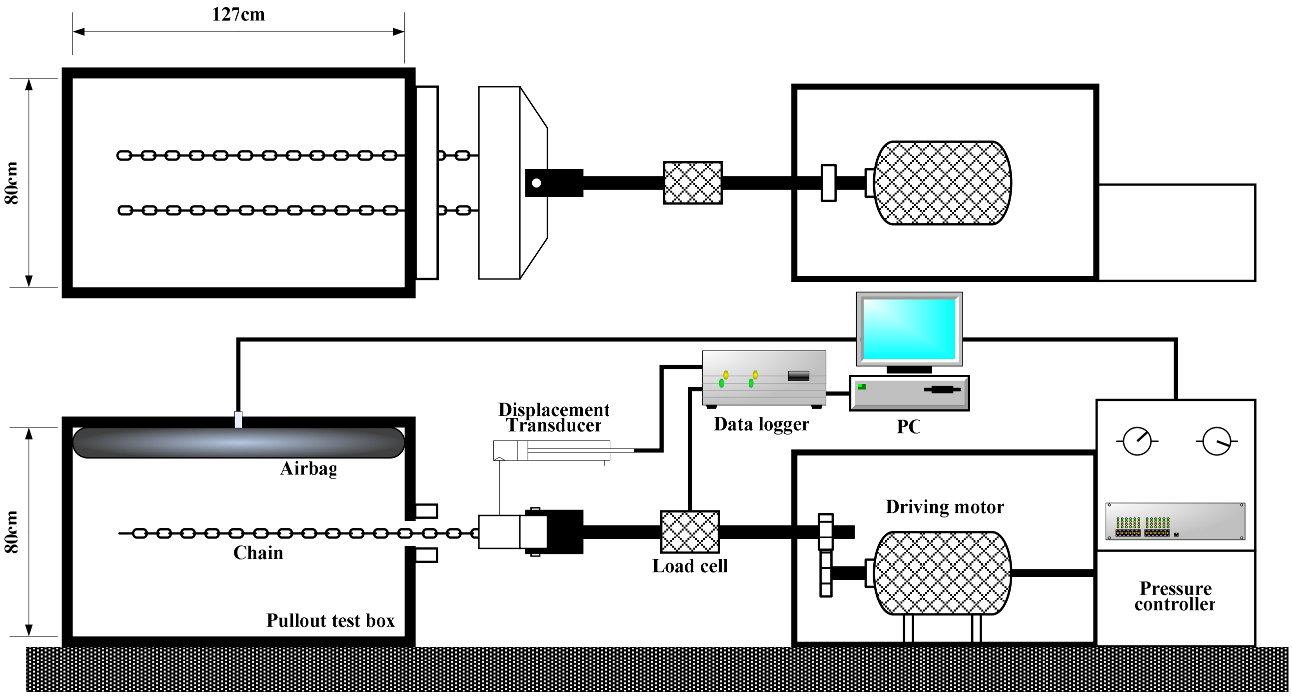

Figure 3. A Schematic diagram of laboratory pullout test equipment.

Table 2. Test conditions for laboratory pullout test.

Type of reinforcement setup	Dimension (mm)		Overburden stress (*kPa*)
Chain	Open chain Closed chain Bar	D = 6.0 D = 6.0 D = 22.0	40
Chain with L-type angle	Chain of D=6.0 L-type steel angle of 4 × 25 × 15		80
Chain with L-type angle and transverse steel bar	Chain of D = 6.0 Transverse steel bar of ϕ = 6.0 L-type steel angle of 4 × 25 × 15		120

chain was used due to practical problems such as loading and work space restriction. Four displacement transducers (two in front and two at the back) were used for the experiment to measure displacement, and the instrument was able to measure a maximum displacement of 205 mm.

Table 2 summarizes the conditions of the laboratory pullout test. The test was conducted for three types of reinforcement as shown in Figure 4 to isolate each factor of pullout resistance. Figure 4(a) represents the case with all three types of pullout resistance factors (open chain), Figure 4b represent the case of the open chain with the interfriction between the soil inside the chain and the surrounding soil removed (closed chain), and Figure 4(c) represent the case of removing all form of resistance other than the friction factor between steel reinforcement and soil (bar). In addition, the type of reinforcement setup was modified to conduct the test using a chain; a chain with L-type angle and transverse steel bar. The test was conducted until the chain was pulled out by the pullout force or the residual pullout resistance with a minimal change in pullout force was shown according to increased displacement. The granite soil, which was used as the fill soil, was compacted to 95%, and compaction was measured for each test based on the fill soil height inside the pullout device and the unit weight

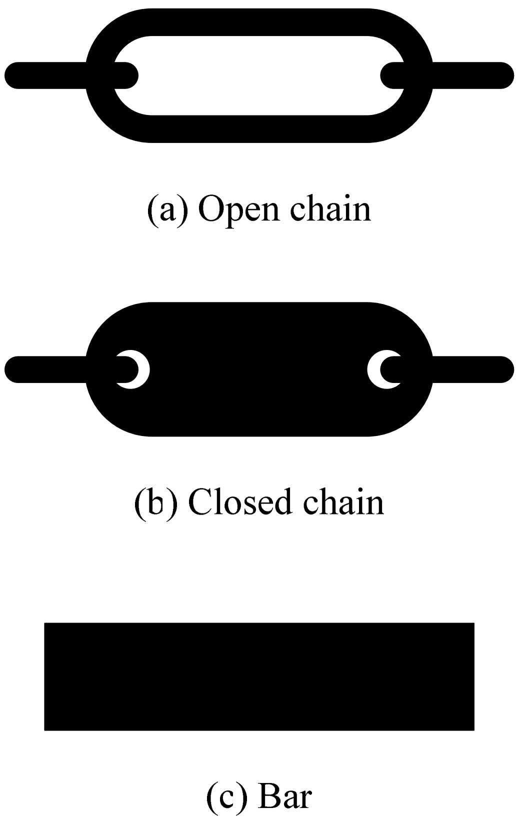

Figure 4. Shapes of various reinforcements.

measurement device.

Relationship between displacement and pullout resistance force

Figure 5(a) show the result of large-scale pullout test conducted with chain only. The displacement indicated in the figure corresponds to front displacement. Rear displacement was not included in the analytical result because it occurred 5 – 10 mm after front displacement. The experimental result indicates that pullout resistance decreases as horizontal displacement increases after the maximum pullout resistance, displaying typical characteristics of soil reinforcement using reinforcement without tensibility. The maximum resistance occurs between 10 and 20 mm. Furthermore, there was a clear indication of stress softening, which involves a rapid decline of pullout force as normal stress is increased after the maximum pullout force. In order to evaluate chain's pullout resistance equation and the pullout resistance according to the type of reinforcement, the pullout test was conducted with the interior closed, and the result is depicted in Figure 5(b). A maximum pullout force of 83.5 - 152.5 kgf occurred at 5.0 - 10.0 mm according to the normal stress. A pullout test was conducted using a 22 mm bar with an identical surface area to comparatively analyze the chain's resistance against pullout force, and the result is indicated in Figure 5(c). It was learned from the experiment that the maximum pullout resistance occurred at a displacement of 1 – 2 mm with a maximum pullout force of 32.5 - 112.5 kgf. Thus the maximum pullout force and deformation were less than those of chain reinforcement (Figure 5).

Since the methods of reinforcement are different, this paper used the bonding coefficient to make comparison under identical conditions. The bonding coefficient represents the bonding level between bearing reinforcement and soil and can incorporate frictional resistance and passive resistance simultaneously. The bonding coefficient can be calculated using Equation (5).

$$f = a_s \tan\delta + \frac{1}{2S}\left(\frac{\sigma_b}{\sigma_v}\right) a_b t \qquad (5)$$

Figure 6 shows the calculation of the bonding coefficient for bar, closed chain and open chain. The bonding coefficient of a bar with diameters of 6 and 22 mm were 0.28 - 0.36 and 0.22 - 0.23, respectively. The bonding coefficient of a bar was inversely proportional to the diameter. The coefficient for a closed chain and an open chain were 0.18 - 0.67 and 0.31 - 0.92, respectively. For a chain, the bonding coefficient was inversely proportional to normal stress. It can be deduced that the interference degree (Koivumäki, 1983) increases with installation spacing and normal stress, reducing passive resistance, which is the second term of the bonding coefficient. The open chain shows a friction force 2.0 - 2.5 and 1.15~1.5 times greater than the bar and the closed chain, respectively.

Figure 7 shows the displacement-pullout resistance relationships of chain and chain with passive reinforcement obtained from pullout test results. Figure 7(a) illustrates the pullout behavior of a chain with a diameter of 6.0 mm. From laboratory experiment, the chain's pullout behavior showed relatively clear yield, ultimate and residual force. The result agrees with other studies conducted using steel reinforcement (Bergado et al., 1992). The maximum resistance was observed at 10 – 20 mm, and resistance rapidly declined after themaximum value. Although only a chain with a diameter of 6.0 mm is displayed here, identical behavior is displayed regardless of the reinforcement diameter and chain breaking was not observed from laboratory experiment. Figure 7(b) shows the experimental result for a case with a chain and a passive reinforcement made with L-type steel angle attached, and the ultimate strength was five times greater than the chain-only case. Although there was sufficient resistance even when there was a substantial displacement (8 - 10 times greater than chain), a very low residual strength was observed compared to the ultimate strength immediately the angle was overturned and

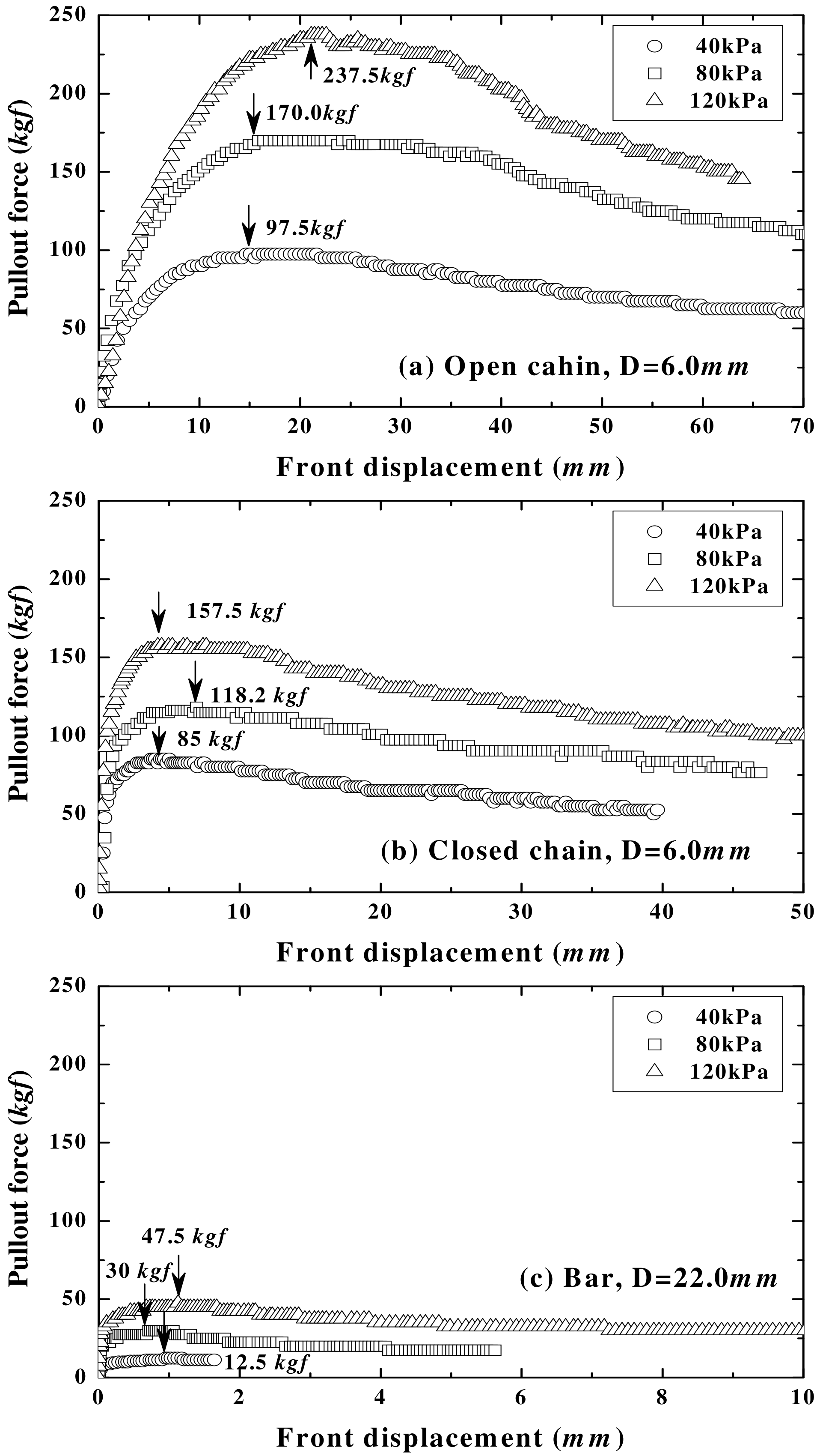

Figure 5. Front displacement-pullout force relationships for various types of steel reinforcement.

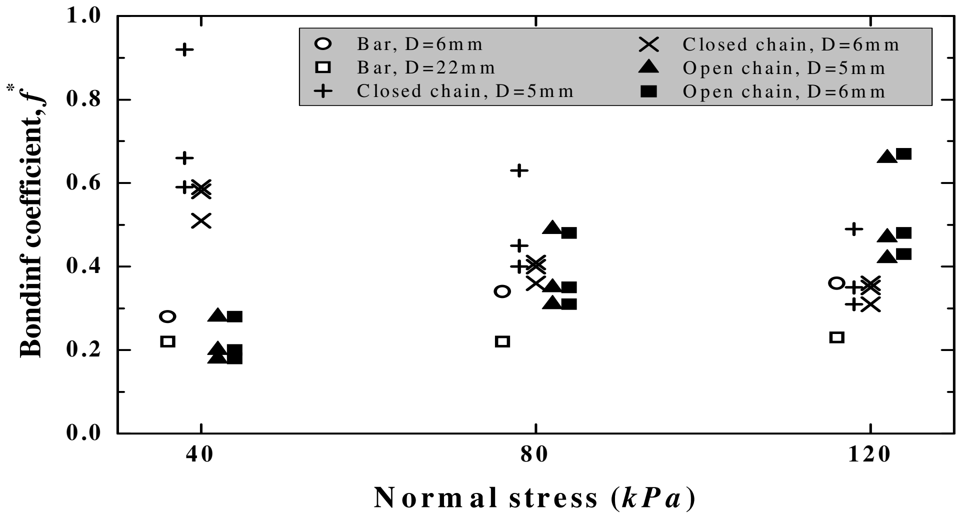

Figure 6. Bonding coefficients for various types of steel reinforcement.

pullout initiated. Figure 7(c) depicts a bar inserted in the lateral direction. Although the pullout properties were somewhat increased compared to Figure 7(b), the increase of the resistive force was not as significant as passive reinforcement such as an L-type steel angle, but there was a substantial improvement from the aspect of residual strength. An obvious result was that pullout resistance characteristics including maximum pullout resistance improved as confining pressure increased under identical conditions.

Comparison between theoretical computation and test result

Pullout resistance of chain was theoretically computed using Equation (2) that incorporates chain's friction resistance and passive resistance as well as pullout resistance (Equations 3 and 4) according to the additionally installed passive reinforcement, and the result was compared with the laboratory experimental result. There was no significant difference between the theoretically computed pullout resistance and the experimental result for the chain-only case and the case of installing additional passive reinforcement. Figure 8 shows the comparison between theoretical and experimental values according to the type of reinforcement. Although the experimental value somewhat exceeded the theoretical value, the two results were almost similar for various overburden pressure conditions. The difference peaked at about 20%.

Despite a slight error, the two values were almost identical, and it was learnt that the three elements regarding pullout (Figure 1) – friction resistance, shear resistance between the soil inside the chain and the surrounding ground, and passive resistance – can be reasonably predicted using the theoretical equation. As it will be explained later, Equations (2) - (4) were obtained by considering three representative pullout resistance elements under the most ideal circumstances, and the laboratory experimental results using similar conditions must correspond with the prediction equations. These observations will be verified again in subsequent *in-situ* experiment.

in-situ PULLOUT TEST

Outlines of *in-situ* pullout test

In-situ test was conducted at a land development site located in Yong-In, Gyeonggi-Do, Korea, and a slit wall was installed to secure a land that is close to a road (Photo 2). The total length was 102 m, with a maximum height of 5.6 m and *in-situ* test was conducted at the center (60 m positions).

The dimensions of the chain used for reinforcement in the test were D = 6 mm, A = 38 mm, a = 26 mm, B = 22 mm and b = 10 mm (Figure 1). A transverse steel bar with a diameter of 6 mm was installed at every 50 cm in the chain's length direction, and an L-type steel angle with a height of 4 cm was installed at the end of the chain. Table 3 outlines the conditions of the *in-situ* test (Table 3).

Pullout test was conducted at 80 locations, while measuring displacement caused by pressure using hollow cylinders with compressors installed as depicted in Photo 3. The hollow cylinder can create a displacement of about 100 mm, and continuous loading is also provided. The test was conducted until residual pullout force was confirmed or chain was broken.

The granite soil used as backfill soil for *in-situ* tests was

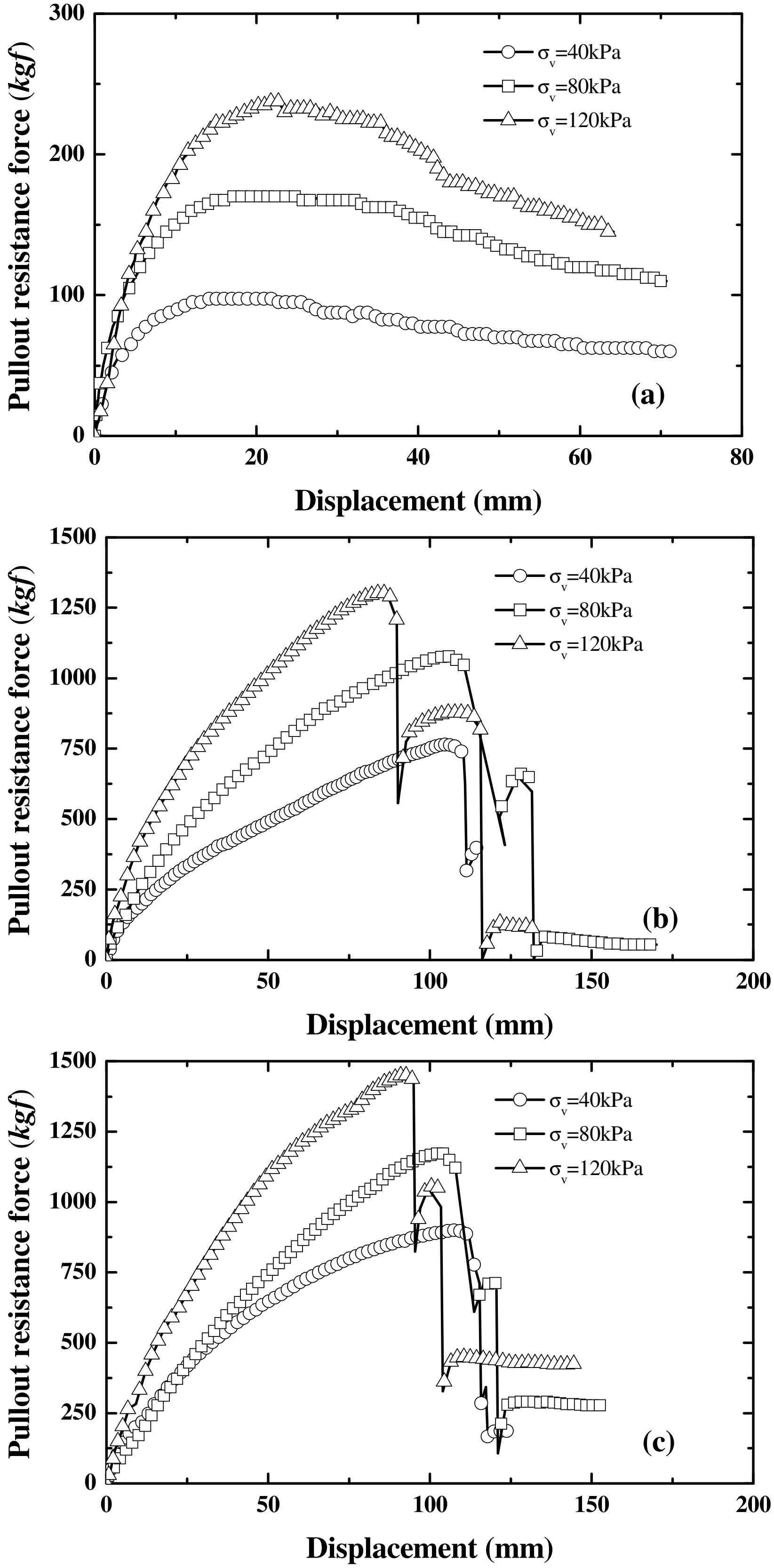

Figure 7. Relationship between displacement and pullout resistance force through laboratory tests: (a) Chain, (b) Chain with L-type angle and (c) Chain with L-type angle and transverse steel bar.

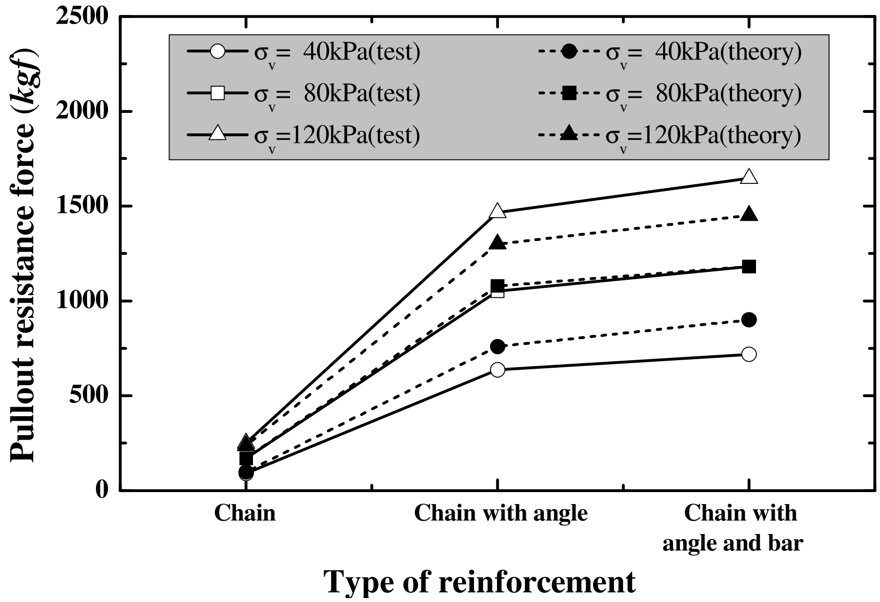

Figure 8. Pullout resistance force with variation in type of reinforcement.

Photo 2. Slit wall constructed in in-situ test site.

Table 3. Test conditions for *in-situ* pullout test.

Type of reinforcement setup	1. Chain (D=6mm) 2. Chain with transverse steel bars 3. Chain with L-type steel angles
Length of reinforcement	2.0, 2.5 and 3.0 m
Embedded depth	2.9 - 4.5 m

Photo 3. Pullout test setup using hollow cylinder.

identical to the soil used in the laboratory test as summarized in Table 1. In the case of internal friction, the average temperature was 38.3°, which was somewhat higher than that of the sample used in the laboratory test (Photos 2 and 3).

Relationship between displacement and pullout resistance force

Table 4 outlines the major results of the *in-situ* pullout tests conducted using the established experimental conditions. Figure 9 shows the load-displacement relationship that summarizes the results obtained with embedded depths of about 3.0 m under similar overburden stress.

The relationship between displacement and pullout force in the laboratory pullout test for geogrid or steel reinforcement, generally provide a relatively clear yield, ultimate and residual force (McGown et al., 1978; Palmeira and Milligan, 1989; Arenicz, 1992), which agreed with the results of this study. However, *in-situ* pullout tests occasionally produce different results. For most experiments conducted for this study, the chain broke (tensile failure), the pullout force consistently increasing as displacement increased and chain being pulled out as shown in the figure. The chain breaking force was about 2150 kgf, and the chain broke around the ultimate strength regardless of its length or the combination of passive reinforcements.

On the other hand, when only chain was used or chain and bar was combined, the displacement of chain breaking was about 150 mm, although the displacement was not consistent. For the case of combining L-type steel angle and chain, breaking occurred around a displacement of 100 mm, which was a 30% reduction compared to chain-only and chain-bar combination, indicating that the angle has an excellent capability to restrain displacement.

It has been reported that when displacement of reinforcement is initiated by pullout force, the confining pressure on the ground around the reinforcement increases not only due to pure normal stress, but also the stress caused by the restrained dilatancy of the surrounding ground for solid sandy soil(FNR Project Clouterre, 1991). Accordingly, reinforcement often breaks rather than being pulled out during pullout tests, and it can be deduced that the chain breaks due to the restrained dilatancy according to the surrounding soil when chain reinforcement is used. Experimental results published by Duncan and Mokwa(2001) indicate that the resistance of an L-type steel angle shows a passive resistance tendency, and it is believed that the experimental results of this study are also based on this tendency.

Figure 9 shows the relationship between pullout force and displacement for each chain length under similar normal load conditions for using chain only and passive reinforcement combinations. The figure demonstrates that the displacement until chain break has little correlation with the chain length, and most breaking occurred around a displacement of 150 mm. This implies that when front displacement reaches an upper threshold, chain's material failure occurs and failure progresses with a mechanism different from that of pullout resistance. In Figure 9(a), with chain lengths of 2.0 and 2.5 m, the chains broke as the load decreased after the ultimate force had been reached. With a chain length of 3.0 m, the ultimate force was never reached, and the chain broke at the displacement of 150 mm while the load was increasing. The pullout forces at breaking were about 1500, 2,000 and 2,250 kg in the order of chain length. In Figure 9(b), the experiment was discontinued for the chain length of 2.0 m because the chain was reduced to

Table. 4. Summary of *in-situ* test results.

Type of reinforcement	length of reinforcement (m)	Embedded depth (m)	Ultimate load (*N*)	D_{UL} (mm)	Yield load (*N*)	D_{YL} (mm)
Chain	2.0	3.1	19,208	76	11,760	72
		3.4	19,208	117	11,760	58
		3.7	22,863	125	12,740	33
		4.0	16,170	80	11,760	42
		4.3	19,110	51	11,760	30
	2.5	3.0	20,580	94	11,760	20
		3.9	19,110	80	13,328	36
	3.0	3.1	22,560	150	13,720	60
		3.5	20,580	120	16,170	66
		3.6	22,050	150	14,700	42
		4.1	22,540	140	13,720	46
		4.5	20,090	100	13,720	41
Chain with transverse steel bars	2.0	3.1	21,756	139	14,700	58
		3.4	20,580	150	14,700	63
		3.7	21,560	130	14,700	48
		4.0	22,540	90	15,680	52
		4.3	22,540	130	17,640	56
	2.5	2.9	21,854	150	13,720	42
		3.8	18,620	160	14,700	68
	3.0	3.1	22,050	126	13,720	46
		3.4	205,800	170	14,210	62
Chain with L-type steel angles	2.0	3.0	22,540	114	13,230	43
		3.3	22,540	180	14,210	51
		3.4	22,540	165	13,720	35
		3.7	22,540	119	14,210	28
		4.3	22,540	200	14,700	64
	2.5	2.8	22,540	100	14,847	45
	3.0	2.9	22,540	100	16,660	48
		3.4	22,050	140	17,640	60

*D_{UL}: Displacement at ultimate load; *D_{YL}: Displacement at yield load.

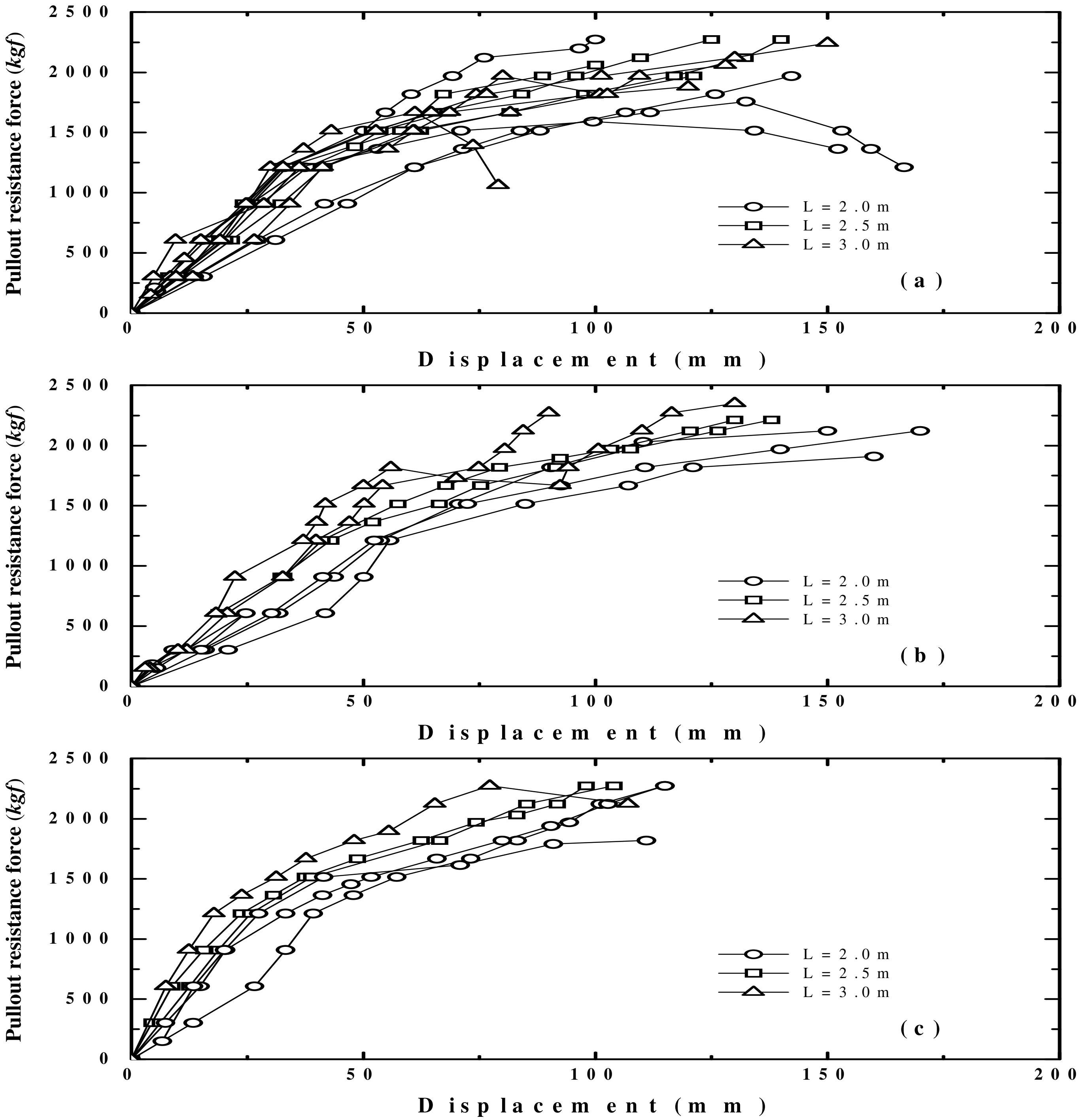

Figure 9. Relationship between displacement and pullout resistance force through *in-situ* tests: (a) Chain, (b) Chain with transverse steel bar and (c) Chain with L-type angle.

the residual force after reaching the ultimate force. When the chain length was 2.5 m, the chain broke a little after the load began to decrease after reaching the ultimate force. When the chain length was 3.0 m, the load continued to increase with displacement and the chain broke close to the displacement of 150 mm.

Comparisons between theoretical estimations and in-situ test results

Table 5 summarizes the pullout resistance values for chain-only cases and passive reinforcement combination cases calculated with Equations (2) - (4). The results in

Table 5. Theoretical estimation of chain type reinforcement.

Length (m)	Overburden stress(kPa)	Pullout resistance force (*N*)				F_{ri} (*N*)	F_{bi} (*N*)	D_{YL} (*mm*)	
		F_1	F_2	F_3	F_{tc}			$F_{tc} + F_{ri}$	$F_{tc} + F_{bi}$
2.0	40	499	668	795	1,963	1,065	947	308.96	296.87
	80	998	1,337	1,591	3,925	1,808	1,884	584.98	593.74
	120	1,497	2,005	2,386	5,888	2,550	2,840	861.01	890.61
2.5	40	622	833	991	2,447	1,065	947	358.37	346.28
	80	1,244	1,666	1,983	4,894	1,808	1,893	683.82	692.58
	120	1,867	2,500	2,974	7,341	2,550	2,840	1009.26	1038.86
3.0	40	745	998	1,188	2,931	1,771	947	407.79	395.70
	80	1,481	1,996	2,375	5,862	1,808	1,893	782.65	791.41
	120	2,236	2,994	3,563	8,794	2,550	2,840	1157.51	1187.11

underestimates chain's resistive capacity against actual pullout.

According to the results of the research conducted by Bergado et al. (1992), Lawson (1992) and FNR Project Clouterre(1991), since frictional resistance occurs on the reinforcement surface along its entire length while the pullout force is acting on inextensible reinforcement like steel, a longer reinforcement shows a greater resistance against pullout and less displacement due to increased confining pressure caused by restrained dilatancy (Sobolevsky, 1995; Hayashi et al., 1997). Thus a chain with inextensible reinforcement properties exhibits confining of reinforcement due to restrained dilatancy that restrains displacement with a higher normal stress, making material breakage a more dominant phenomenon that a failure due to pullout.

Figure 10 shows the results of chain-bar combination and chain-L-type steel angle combination, respectively. The yield force for both cases was slightly higher than using a chain alone, and the rates of increase for bar and angle were similar. The magnitude of the yield pullout force was about 1200 – 1800 kgf depending on the reinforcement method or normal stress. This is 1.2 - 3 times greater than calculated values, indicating that the yield stress is greater for a higher normal stress, a longer chain and when passive reinforcement is combined.

Conclusions

This study evaluated the pullout resistive force when chain was used as reinforcement on the soil reinforcement retaining wall system based on *in-situ* experiments, and the results can be summarized as follows:

1. Laboratory experiments indicate that stress softening, which involves a rapid decline of pullout resistance after reaching maximum pullout resistance was more evident for an open chain than a closed chain or a bar.
2. The bonding coefficient was calculated to comparatively analyze the resistance efficiencies of different types of reinforcement based on the laboratory pullout test results. It was found that the bonding coefficient of a chain with passive resistance was 2.0 - 2.5 times greater than that of a bar based on skin friction, and the bonding coefficient of an open chain was 1.15 - 1.5 times greater than that of a closed chain.
3. The displacement-pullout force relationship obtained from *in-situ* pullout tests indicated that the load consistently increased up to about 150 mm in most cases and broke (tensile failure) when the ultimate pullout force was reached.
4. As for the experiment conducted with a bar attached as passive reinforcement to the chain, the displacement-pullout force relationship was similar to using chain alone, and the yield pullout force was slightly increased. Thus it was determined that pullout force was applied, while

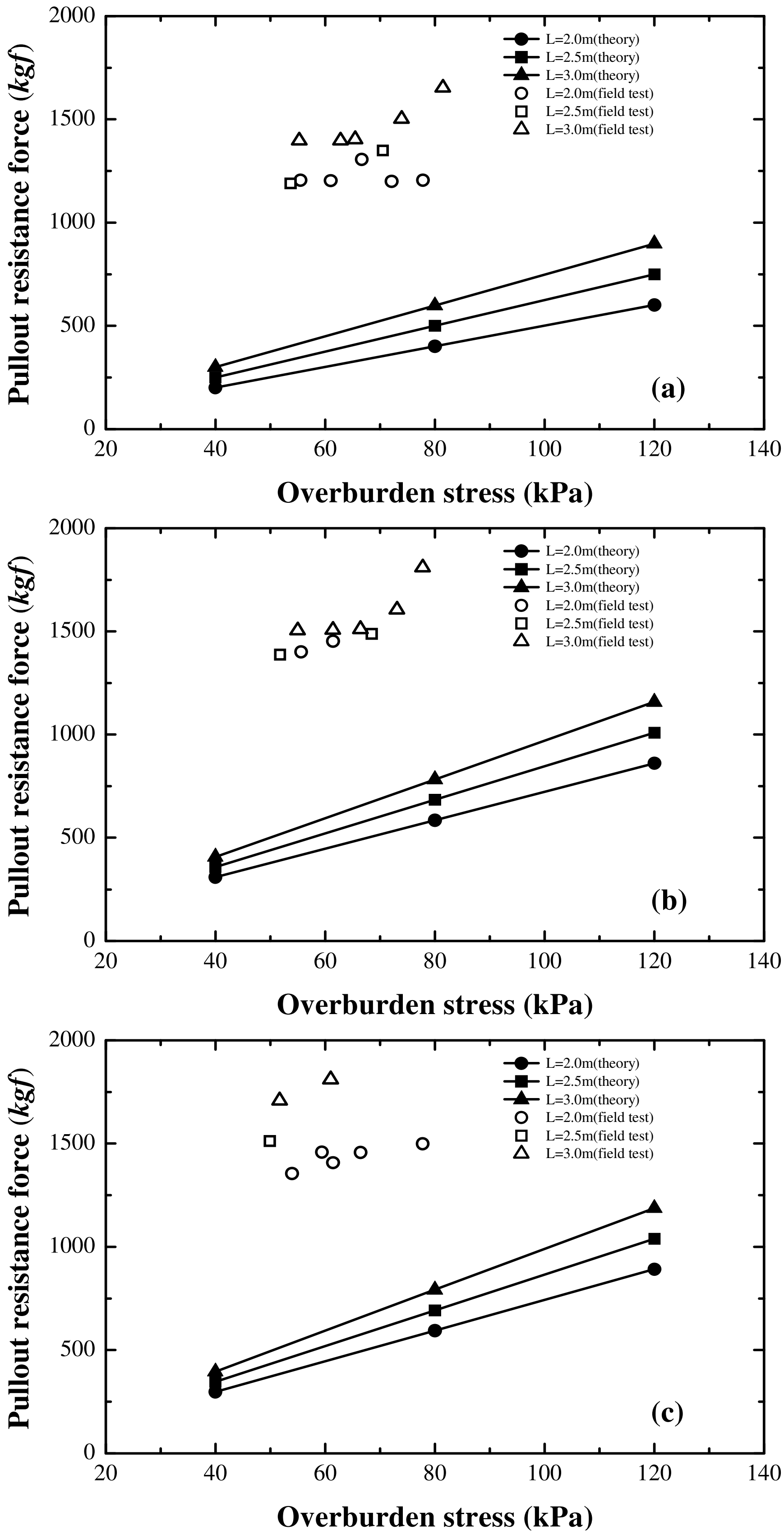

Figure 10. Comparison between *in-situ* pullout test and theoretical computation: (a) Chain, (b) Chain with transverse steel bar and (c) Chain with L-type angle.

pullout resistance was shown throughout the chain, which is an inextensible reinforcement. It was found that a bar had little effect on chain displacement.

5. When an L-type steel angle was used as passive reinforcement, displacement was reduced by about 30% from using chain alone, and the yield pullout force increased slightly. Thus it was determined that an L-type steel angle has a significant influence of chain's displacement, and the resistance of the L-type steel angle is highly likely to be passive resistance that requires a relatively small displacement compared to bearing resistance.

6. Comparing theoretical and measured values, the measured yield pullout force was 1.2 - 3 times greater than theoretical values depending on the reinforcement method or normal stress. The result indicates that the yield stress is greater for a higher normal stress, a longer chain and when passive reinforcement is combined. The difference was not significant between bar and L-type steel angle in terms of the increase of the yield pullout force.

Although designs and constructions using chain as reinforcement and applying conventional theoretical equations were deemed safe, it was determined that chain's pullout force is underestimated. Accordingly, more detailed tests need to be conducted for the pullout resistance of chain-only cases to achieve economical design and construction.

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