Water Sealing by Wire Brush with Grease for Pneumatic Caisson Method at Great Depth Underground

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ABSTRACT: Pneumatic caisson method can be widely applied to various ground and has high reliability, while its applicable depth is limited due to the work under high atmospheric pressure. To overcome the problem, the pneumatic caisson method employing an unmanned excavation method with helium mixed gas has been developed, which enables the work under pressure up to 0.7 MPa. However, the new technology of the pneumatic caisson method will be required to construct a vertical shaft for urban tunnels at great depth underground space. Therefore, applying water-sealing technique at shield tail to friction cut space around pneumatic caisson wall, a method to reduce atmospheric pressure in a working chamber at the ground with low permeability has been proposed. This research carried out the element tests to examine the water-sealing performance of the proposed method, and discussed the influence of some properties on water-sealing performance and its mechanism. As a result, it was confirmed that the proposed method can keep the grease pressure of 1 MPa for one hour.

KEYWORDS: Pneumatic caisson method, Great depth underground, Water sealing, Wire brush, Grease

1. INTRODUCTION

Pneumatic caisson method can be widely applied to various ground and has high reliability, while its applicable depth is limited due to the work under high atmospheric pressure (JSCE 2006). To overcome the problem, the pneumatic caisson method employing an unmanned excavation method with helium mixed gas has been developed, which enables the work under atmospheric pressure up to 0.7 MPa (JSCE 2015). However, the new technology of pneumatic caisson method will be required to construct a vertical shaft for urban tunnels at great depth underground space with a groundwater level of 100m, which will appear at the Maglev project in Tokyo and the Tokyo outer ring road project etc.

In the case of shield tunnelling method, water sealing between segment and tail skinplate is usually ensured by injecting grease between wire brushes at shield tail during TBM advance as shown in Figure 1 (Hirai et al. 2011a; Hirai et al. 2011b; Sugimoto et al. 2014). Applying this water-sealing technique to the friction cut space between pneumatic caisson wall and ground with low permeability, as shown in Figure 2, a method to reduce the atmospheric pressure in a working chamber for one hour, which is the expected manual maintenance work time at excavation stop, has been proposed. Therefore, to make clear the water-sealing performance of the proposed method quantitatively, the first phase element tests using a standard size wire brush for an ordinary TBM and an ordinary tail grease (hereafter called “Phase 1 test”) were carried out. After that, using the modified wire brushes by the examination of Phase 1 test, the second phase element tests (hereafter called “Phase 2 test”) were carried out. In this study, the following test parameters were adopted: 1) the shape of surface plate of wire brush; 2) the roughness of excavation surface around pneumatic caisson wall; and 3) the tail clearance.

This paper shows the above element test results and discusses the influence of test parameters on water-sealing performance of the proposed method and its mechanism.

2. METHODOLOGY

The space between pneumatic caisson wall and ground is filled up by ground water, grease, and air from the top to the bottom, as shown in Figure 2. Since the grease pressure, σ_g, the hydraulic water pressure, σ_w, and the atmospheric pressure in a working chamber, σ_{air}, become smaller in this order in the proposed method, and σ_g and σ_{air} provide the largest different pressure at the both sides of wire brush, the element tests on the water-sealing performance of the proposed method were carried out, focusing on σ_g and σ_{air}.

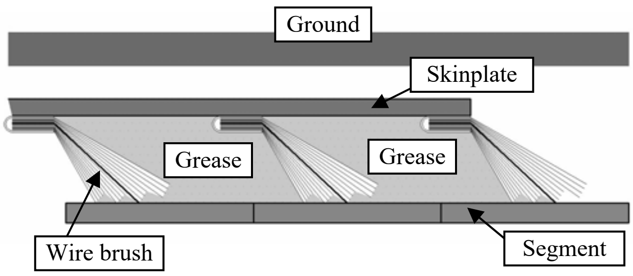


Figure 1 Detail of shield tail

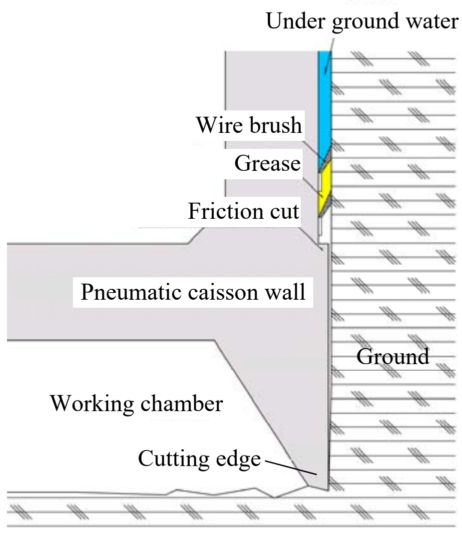
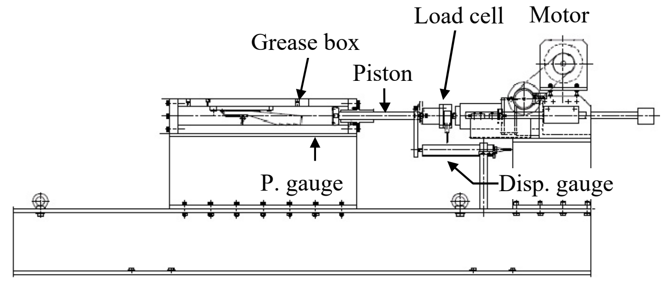


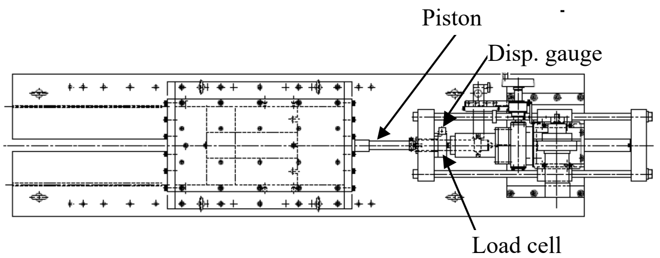
Figure 2 Schematic view of the proposed water-sealing method

2.1 Test equipment

The test equipment is composed of an upper plate with wire brushes, a steel box where grease and wire brushes are installed (hereafter called grease box), and a piston to press grease in horizontal direction with a specified velocity, as shown in Figure 3. Here, three wire brushes with a width of 100 mm (hereafter called WB) were used in the test equipment with a width of 300 mm. In the test, the tail sealer #8000N and #8000NP (Matsumura Oil Chemical 2013) were used as grease. Considering the temperature dependency of the grease viscosity, the tests were carried out in a constant temperature room (20℃). The grease pressure σ_g generated by the piston was regarded as the bearing hydraulic water pressure σ_w by one layer of the wire brush.



(a) Side view.



(b) Plain view.

Figure 3 Test equipment

2.2 Measurement

The following items shown in Table 1 were measured automatically by a data logging system.

1. Piston horizontal displacement: the piston position in horizontal direction was measured by a displacement gauge to grasp the grease flow.
2. Piston thrust: the piston thrust was measured by a load cell to grasp the grease pressure.
3. Grease pressure: five water pressure gauges were set at the bottom of the grease box to grasp the grease pressure distribution, as shown in Figure 4.

Table 1 Measurement list

Item	Instrument	No.	Capacity
Disp. of piston	Disp. gauge	1	100 mm
Thrust of piston	Load cell	1	49.03 kN
Grease pressure	Pressure gauge	5	5000 kPa

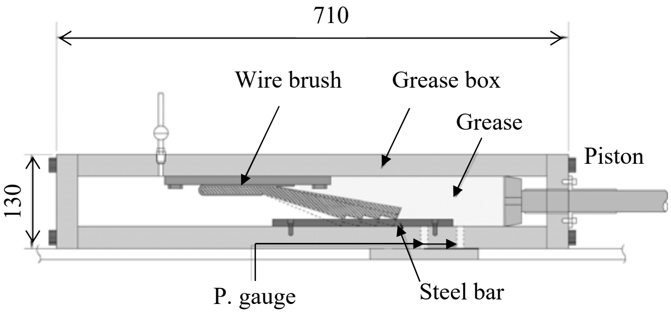
2.3 Test parameters

The following three parameters were adopted as test parameters.

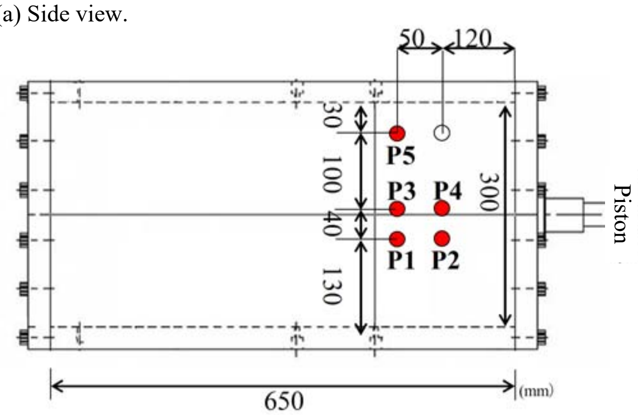
2.3.1 Shape of surface plate of wire brush

At first, three types of WB (WB1, WB2 and WB3) as shown in Table 2 were set, based on a standard size wire brush for an ordinary TBM, since the fitting ability of WB to the bottom surface and the bending stiffness of surface plate of WB are considered to give the influence on the water-sealing performance of WB. Here, the fitting ability was realized by the slits at the inner surface plate as shown in Figure 5.

After Phase 1 test, another two types of WB (WBS and WBL) as shown in Table 2 were added, based on the examination at Phase 1 test, of which the detail will be described in Chapter 4.



(a) Side view.



(b) Plain view.

Figure 4 Grease box

Table 2 Wire brush type (WB type) (mm)

Type	Slit at inner surface plate	Protection cloth	Inner plate		Outer plate	
			Length	Thickness	Length	Thickness
1	None			0.5		1.0
2	10mm interval*1	None	120	0.5	175	0.5
3				1.0		1.0
S	10mm interval *1	220	120	0.5	200	1.0
L		260	160	0.5	240	1.0

*1: No slit in 4cm width from the edge

2.3.2 Roughness of excavation surface around pneumatic caisson wall

Three steel bars with a rectangular cross section were set on the bottom of the grease box, as shown in Figure 6, to simulate the roughness of excavation surface around pneumatic caisson wall, since the roughness of excavation surface influences the water-sealing performance of WB. Here, the steel bar is 250 mm in length, and its cross section and its position are shown in Table 3, which require the excavation control with high accuracy.

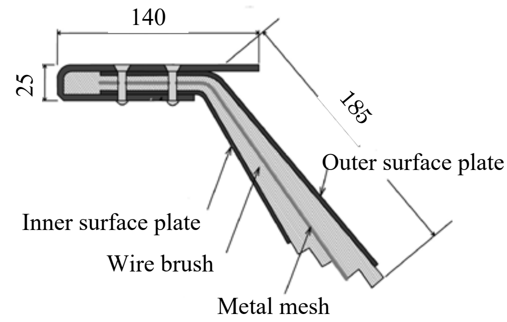
2.3.3 Tail clearance

The tail clearance of 50 mm and 70 mm were used by setting a spacer at the bottom of the grease box, since the tail clearance influences the water-sealing performance of WB.

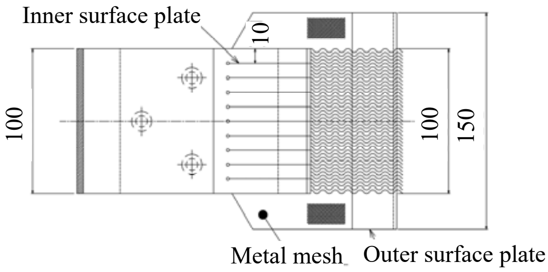
2.4 Test procedure

The element tests were carried out by a displacement control method and a stress control one. Note that the stress control method is similar to a control at a site.

The test procedure by the displacement control method is as follows as shown in Figure 7:



(a) Side view.



(b) Plain view.

Figure 5 Wire brush (WB3)

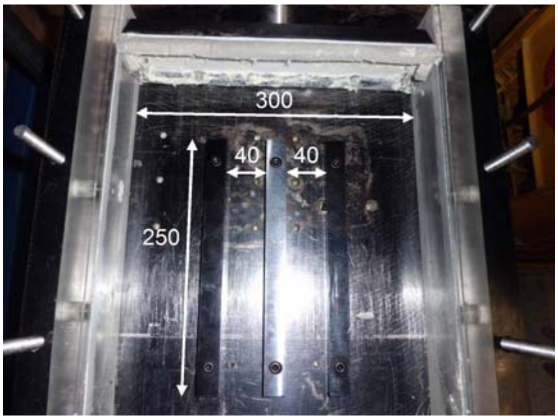


Figure 6 Steel bars setting on the bottom of the grease box (M2)

Table 3 Excavation surface type (M type)

Type	Interval (W)	Height (H)	Cross section
M0 Flat	–	–	
M1 W20×H10	20 mm	10 mm	
M2 W40×H10	40 mm	10 mm	
M3 W40×H20	40 mm	20 mm	

1. Fill up the inside of the WB with the grease ＃8000N, and fill up the space between the WB and the piston in the grease box with the grease ＃8000NP by hand pressing. After filling up, the upper plate is attached to the grease box.
2. Start a test by pushing the piston to the WB with a specified speed. Here, the piston speed 3.0 mm/min was in use, which corresponds to the maximum grease supply capacity at an actual condition.
3. Stop the piston when the following conditions are satisfied: 1) the piston displacement reaches 100 mm, which is the maximum stroke of the piston; 2) the peak of σ_g appears, since it means that the grease leakage flow is over the maximum grease supply capacity and the increase of σ_g under the same condition cannot be expected; and 3) σ_g reaches 1.5 MPa, which is equal to the safety factor (1.5) times the target bearing hydraulic water pressure σ_w (1.0 MPa) in this test. Note that the capacity of σ_g of this test equipment is 2.38 MPa.
4. Continue the measurement for one hour after piston stop, which corresponds to the manual maintenance work time in the work chamber at the caisson bottom.

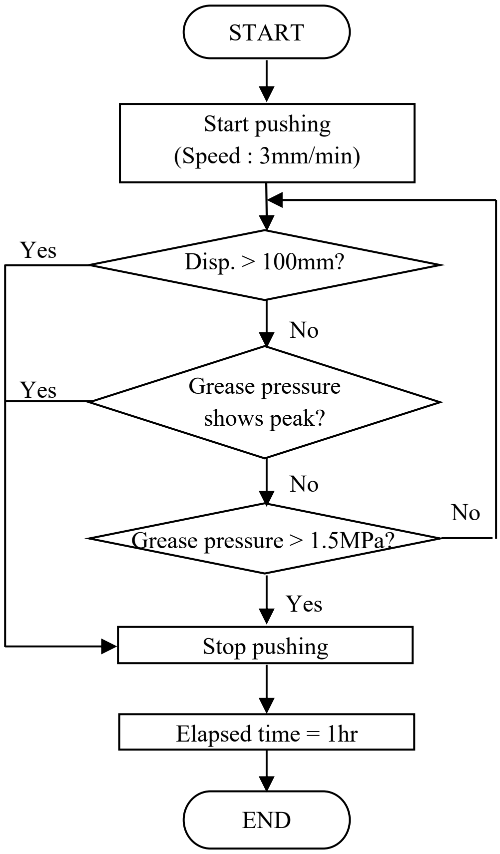


Figure 7 Flow of test procedure (Displacement control)

On the other hand, the test procedure by the stress control method is as follows as shown in Figure 8:

1. Fill up the inside of the WB and the grease box with the grease like the displacement control method.
2. Increase the grease pressure up to a control value (1.0 MPa) like the displacement control method.
3. After the grease pressure reaches the control value, change the control method from the displacement control method to the stress control method, and keep the grease pressure of a constant value (1.0 MPa) for one hour, which correspond to the manual maintenance work time in the work chamber, by the feedback control using the measured grease pressure.
4. Continue the measurement for one hour after piston stop.

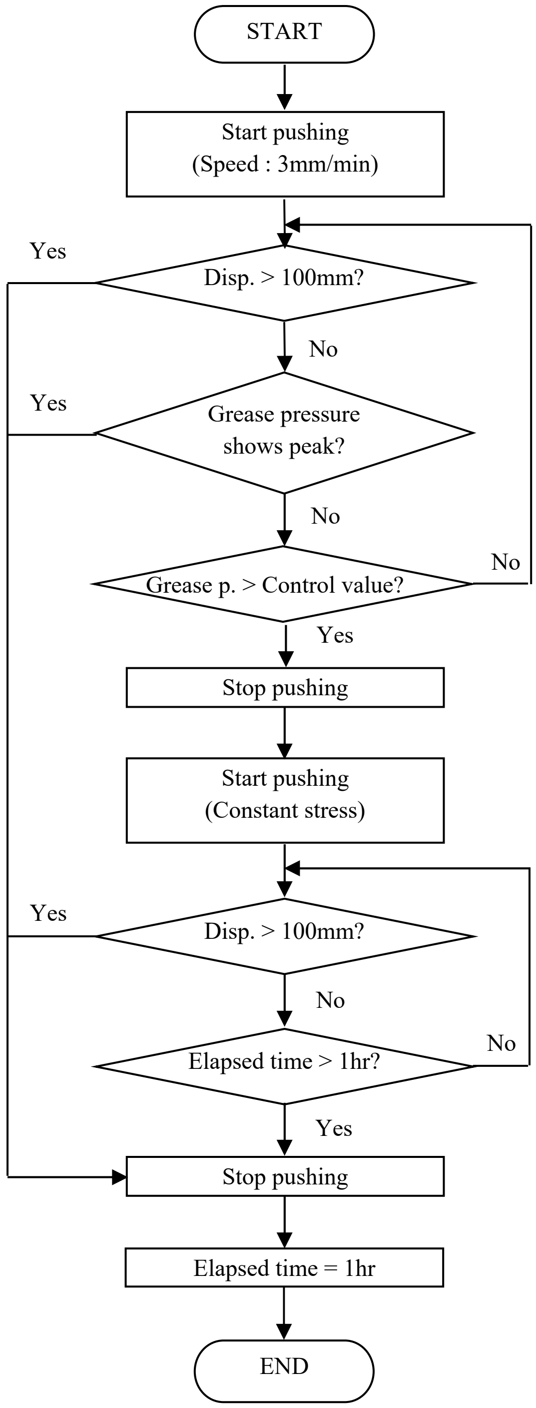


Figure 8 Flow of test procedure (Stress control)

3. PHASE 1 TEST

3.1 Test conditions

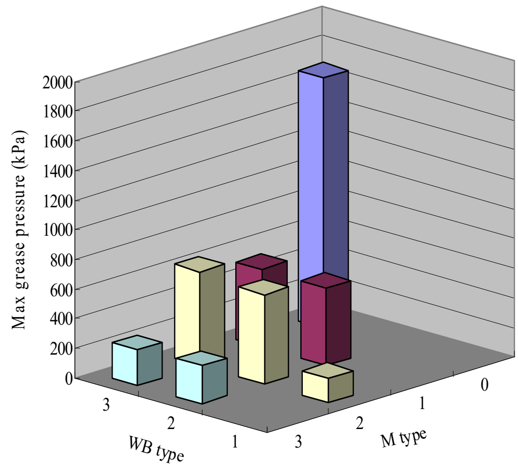
Phase 1 test is like a preliminary element test using a standard size wire brush for an ordinary TBM (Kawasaki et al. 2013). Therefore, three types of WB (WB1, WB2 and WB3) in Table 2, four excavation surface types in Table 3 and the tail clearance of 50 mm and 70 mm were used. As for the test procedure, the displacement control method in Figure 7 was applied.

3.2 Influence of test parameters on water-sealing performance

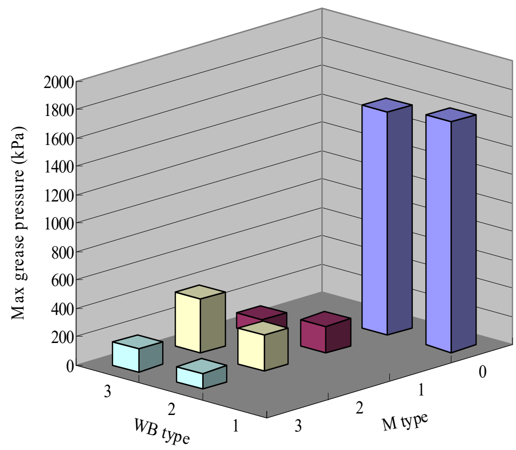
Table 4 shows the maximum grease pressure, σ_{gmax}, the residual grease pressure after one hour from piston stop, σ_{gres}, and the residual rate of grease pressure, which shows the ability to keep σ_g without grease supply and is define as σ_{gres} is divided by σ_{gmax}. Figures 9 and 10 show the maximum grease pressure, σ_{gmax} and the residual grease pressure, σ_{gres}.

Table 4 Maximum grease p. and residual grease p. (Phase 1)

Tail clearance (mm)	WB type	M type	Grease pressure(kPa)		Residual rate (%)
			Max	Residual	
50	1	2	169	57	34
	2	1	524	99	19
		2	608	106	17
		3	257	60	23
	3	0	1690	806	48
		1	527	121	23
		2	638	128	20
		3	238	62	26
70	1	0	1623	686	42
	2	0	1570	718	46
		1	189	63	33
		2	251	83	33
		3	114	54	47
	3	1	107	41	38
		2	381	72	19
		3	162	52	32

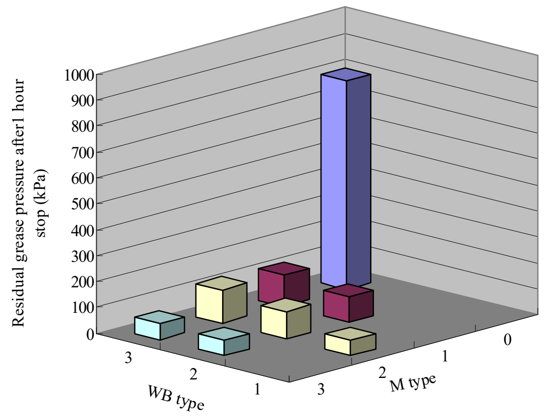


(a) T_c = 50mm

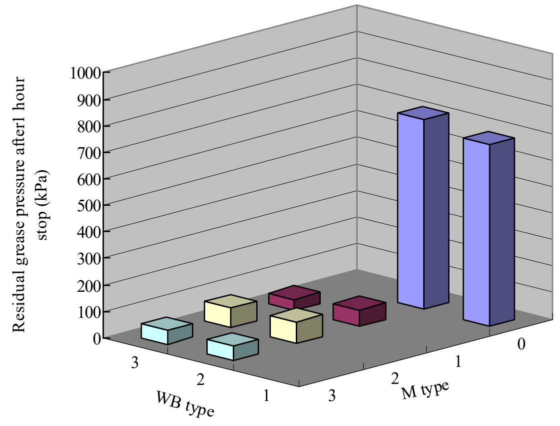


b) T_c = 70mm

Figure 9 Maximum grease pressure



(a) T_c = 50mm



(b) T_c = 70mm

Figure 10 Residual grease pressure after 1 hour from piston stop

From Table 4 and Figure 9, as for the maximum grease pressure, σ_{gmax}, the following were found:

1. The excavation surface is flat (M0): In the case of the tail clearance T_c = 70 mm and the WB with/without slit (WB1/WB2), which is expected to be the lowest sealing performance of WB among the test cases of M0, the σ_{gmax} was larger than 1.5 MPa, which is the condition of piston stop. Then the other test cases using the excavation surface type M0 were skipped.
2. The WB without slit (WB1): In the case of T_c = 50 mm and the excavation surface type M2, which is expected to be the highest sealing performance of WB among the test cases of WB1, the σ_{gmax} was less than 200 kPa. Then the other test cases using WB1 were skipped.
3. The shape of surface plate of WB: In the case of T_c = 50 mm and the excavation surface type M2, the σ_{gmax} of WB2 and WB3 were larger than 500 kPa, while that of WB1 was less than 200 kPa. Furthermore, in the case of T_c = 50 mm, the σ_{gmax} of WB2 was almost the same as that of WB3, but in the case of T_c = 70 mm, the σ_{gmax} of WB2 was less than that of WB3. These indicate that 1) slit can increase the sealing performance of WB; and 2) higher bending stiffness of surface plate can increase it under the larger tail clearance.
4. The roughness of excavation surface: In the case of T_c = 50 mm, the σ_{gmax} became smaller in the order of the excavation surface type M2, M1 and M3, while in the case of T_c = 70 mm, the σ_{gmax} with the excavation surface type M2 was much larger than those with the excavation surface types M1 and M3. These indicate that 1) σ_{gmax} is smaller, as the height of roughness is higher and the width of roughness is narrower, since the WB slit hardly follows the roughness; and 2) the larger T_c relieves the effect of the height of roughness on σ_{gmax}.
5. The tail clearance: the σ_{gmax} of T_c = 50 mm was larger than that of T_c = 70 mm. This is because the contact force between the WB and the grease box by the outer surface plate, and the contact length of the WB with the grease box become larger, as the T_c is smaller.

From Table 4 and Figure 10, as for the residual grease pressure after one hour from piston stop, σ_{gres}, the following were found:

1. The σ_{gres} is much smaller than the σ_{gmax}, that is, the residual rates are less than 50%, especially in the case of the excavation surface type M1, M2 and M3. The residual rate is smaller, as the σ_{gmax} is larger.
2. The influence of the test parameters on the σ_{gres} is similar to that on the σ_{gmax}.

For example, Figure 11 shows the time dependent grease pressure, σ_g, in the case of T_c = 50 mm, the WB type WB3, and the excavation surface type M2, which shows the maximum σ_g among the test cases except for the excavation surface type M0. From this figure, after the piston stop, the σ_g drops down rapidly and converges to a certain low value. This is considered to result from the leakage of grease.

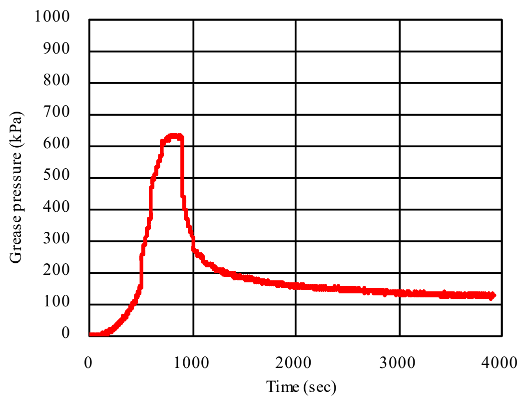


Figure 11 Time dependent grease pressure (T_C50mm, WB3, M2)

3.3 Mechanism of grease leakage

Figure 12 is the photo on two major patterns of grease leakage, and Figure 13 shows the concept of grease leakage mechanism. From these figures, the following were considered:

1. Patter 1: Grease leaks from the upper part of the steel bar, since the gap between the inner surface plate and the steel bar appears due to slit twist; and
2. Patter 2: Grease leaks from the side of the steel bar, since the open space at a slit appears due to the bump surface, as shown in Figure 14.

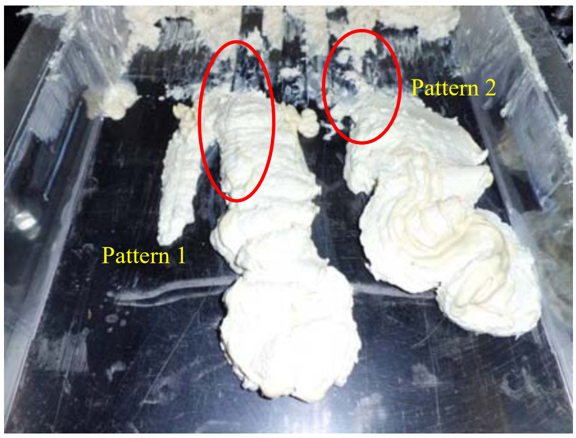


Figure 12 Grease leakage pattern after test

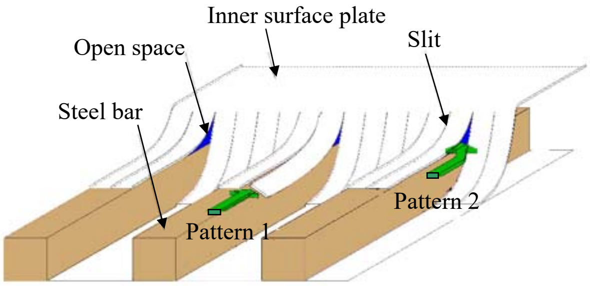


Figure 13 Concept of grease leakage pattern

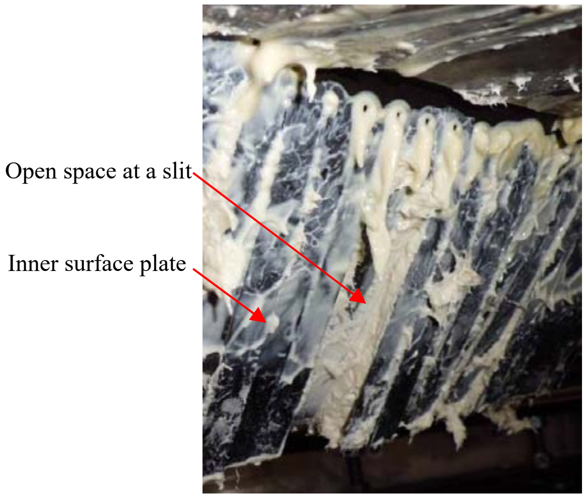


Figure 14 Inner surface plate with slit after test

3.4 Summary

The results at Phase 1 test can be summarized as follows:

1. The better fitting of WB to excavation surface, that is, the WB with slits, the high contact force of WB to excavation surface, and the longer contact length of WB with excavation surface, provide higher water-sealing performance.
2. It is important to reduce the gap between the inner surface plate and the excavation surface and the open space at a slit, to ensure high water-sealing performance.
3. The σ_{gmax} is smaller, as the height of roughness is higher, the width of roughness is narrower, and the tail clearance is larger.
4. In some cases, such as, the tail clearance T_c = 50 mm, the excavation surface type M3, and the WB with slit (WB2 or WB3), the bearing hydraulic water pressure σ_w by one layer of WB is larger than 200 kPa. Therefore, when several layers of WB with grease are set along a pneumatic caisson wall in vertical direction, the decreasing ground water pressure σ_w by the proposed method is expected to be more than 300 kPa, which is the target of this method. But it is necessary to improve the water-sealing performance.

4. PHASE 2 TEST

4.1 Test conditions

At Phase 2 test, based on the examinations at Phase 1 test, the WB was improved as follows as shown in Table 2:

1. Flexible protection cloth with folds made of aramid fiber is set just behind the inner surface plate, to escape the grease leakage, even the gap between the inner surface plate and the excavation surface and the open space at a slit are generated.
2. .The inner surface plate and the outer surface plate was made longer, to improve the fitting of WB to the excavation surface.
3. The thickness of the inner surface plate and that of the outer surface plate were 0.5 mm and 1.0 mm, respectively, taking account of the following: 1) in the case of a thick surface plate, high water-sealing performance is expected due to the high contact force of WB to the excavation surface; and 2) in the case of a thick surface plate, the damage of the surface plate and its plastic deformation appear more.

Therefore, two types of the improved WB (WBS and WBL) in Table 2, four excavation surface types in Table 3 and the tail clearance T_c of 70 mm were used. Here, it is noted that T_c = 70 mm is more severe condition than T_c = 50 mm from the viewpoint of the water sealing performance. Furthermore, not only the displacement control method in Figure 7 but also the stress control method in Figure 8 were applied, to check the performance of the proposed method under a similar condition at a site.

4.2 Test results by displacement control method

Table 5 shows the maximum grease pressure, σ_{gmax}, the residual grease pressure after one hour from piston stop, σ_{gres}, and the residual rate of grease pressure by the displacement control method and the stress control method, adding the test results of WB2 and WB3 at Phase 1 test as reference.

Table 5 Max grease p. and residual grease p. (Phase 2)

Control	WB type	M type	Grease p.(kPa)		Residual
			Max	Residual	rate (%)
Disp.	2*1	0	1570	718	46
		1	189	63	33
		2	251	83	33
		3	114	54	47
	3*1	1	107	41	38
		2	381	72	19
		3	162	52	32
	S	0	1500	1185	79
		1	1500	843	56
		2	1500	721	48
		3	329	82	25
	L	0	1500	983	66
		1	1500	810	54
		2	1500	287	19
		3	1500	774	52
Stress	S	1	1000	320	32
		2	1000	766	77
		3	—	—	—
	L	1	1000	763	76
		2	1000	750	75
		3	1000	772	77

*1: The results at Phase1 test are shown.

4.2.1 Maximum grease pressure

Figure 15 shows the maximum grease pressure, σ_{gmax}, by the displacement control method. From Table 5 and Figure 15, the following were found:

1. The excavation surface is flat (M0): All of the WB type have enough water-sealing performance for the flat excavation surface (M0), since the σ_{gmax} was larger than 1.5 MPa, which is the condition of piston stop.
2. The roughness of excavation surface: The σ_{gmax} became smaller in the order of the excavation surface type M2, M1 and M3. This indicates that σ_{gmax} is smaller, as the height of roughness is higher and the width of roughness is narrower, since the WB slit hardly follows the roughness.
3. The WB type: The σ_{gmax} became smaller in the order of the WB type WBL, WBS, WB3 and WB2. This indicates that 1)

the WBL and WBS, which have the stiff surface plate with slits and the flexible and strong protection cloth, provide higher σ_{gmax}, since they can reduce the gap between the inner surface plate and the excavation surface and the open space at a slit, compared with the WB3 and WB2, which have the stiff surface plate with slits only; and 2) σ_{gmax} becomes larger, as the length of the inner surface plate and the outer one is longer.

4. Furthermore, the improved WB at Phase 2 test (WBL and WBS), except for the case of the WBS and the excavation surface type M3, have enough water-sealing performance for any excavation surface type even the T_c = 70 mm, since all of the σ_{gmax} reached 1.5 MPa, which is the condition of piston stop.

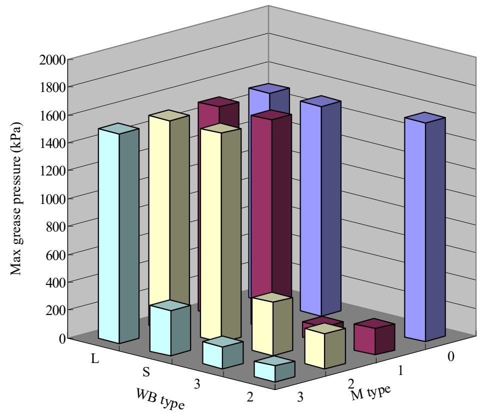


Figure 15 Maximum grease pressure (Disp. Control)

4.2.2 Residual grease pressure

Figure 16 shows the residual grease pressure after one hour from piston stop, σ_{gres}, by the displacement control method. From Table 5 and Figure 16, the following were found:

1. In the case of the WBL, and the WBS except for the excavation surface type M3, the σ_{gres} is larger than 287 kPa, while in the case of the WB2, and the WB3, the σ_{gres} is less than 83 kPa.
2. The influence of the test parameters on the σ_{gres} is similar to that on the σ_{gmax}.

These can be explained in the same way as the σ_{gmax}.

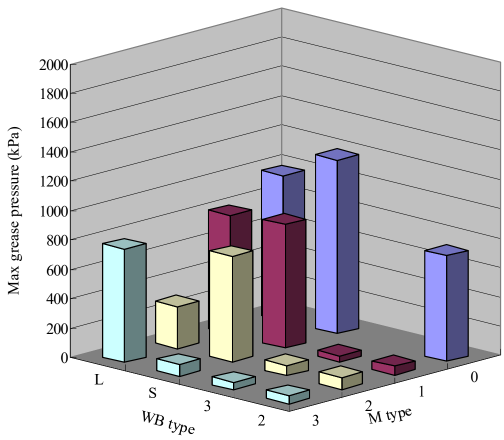


Figure 16 Residual grease p. after 1 hour from piston stop (Disp. Control)

4.3 Test results by stress control method

The maximum grease pressure, σ_{gmax}, the residual grease pressure after one hour from piston stop, σ_{gres}, and the residual rate of grease pressure by the stress control method are also shown in Table 5.

4.3.1 Maximum grease pressure

From Table 5, the following were found:

1. The improved WB at Phase 2 test (WBL and WBS), except for the case of the WBS and the excavation surface type M3, have enough water-sealing performance for any excavation surface type even the T_c = 70 mm, since all of the σ_{gmax} reached 1.0 MPa, which is the control value in the stress control method.

4.3.2 Residual grease pressure

Figure 17 shows the residual grease pressure after one hour from piston stop, σ_{gres}, by the stress control method. From Table 5 and Figure 17, the following were found:

1. In the case of the WBL for any excavation surface type, the σ_{gres} is larger than 750 kPa and the residual rate of grease pressure is larger than 75 %. This means that the WBL has enough water-sealing performance for one hour even without grease supply.
2. In the case of the WBS, the σ_{gres} for the excavation surface type, M2 and M1 are 1.0 MPa and 320 kPa respectively. The test using the WBS and the excavation surface type M3 was terminated before the stress control method, since the σ_{gmax} did not reach the control value 1.0 MPa.

These can be explained in the same way as the σ_{gmax}.

4.3.3 Time dependent grease pressure

For example, Figure 18 shows the time dependent grease pressure, σ_g, in the case of T_c = 70 mm, the WB type WBL, and the excavation surface type M3, which shows the maximum σ_{gres} among the test cases. From this figure, the following were found:

1. At first 1000 sec, the loading speed (tat is, piston speed) is 3.0mm/min by the displacement control method. After the σ_g reaches 1.0 MPa, the σ_g keeps 1.0 MPa for one hour by the stress control method. After the piston stop, the σ_g decreases gradually up to 772 kPa for one hour.
2. During the stress control, the loading speed is close to 0.0mm/min, that is, the σ_g can keep 1.0 MPa with a little grease supply.

These indicates the following:

1. The proposed method has a possibility to be applied to the pneumatic caisson method for the ground with high groundwater level.
2. The grease supply for water-sealing can be saved, when the water-sealing performance of the proposed method is high.

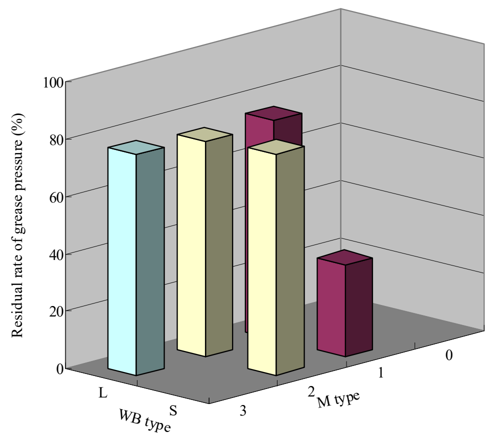


Figure 17 Residual rate of grease p. after 1 hour from piston stop (Stress Control)

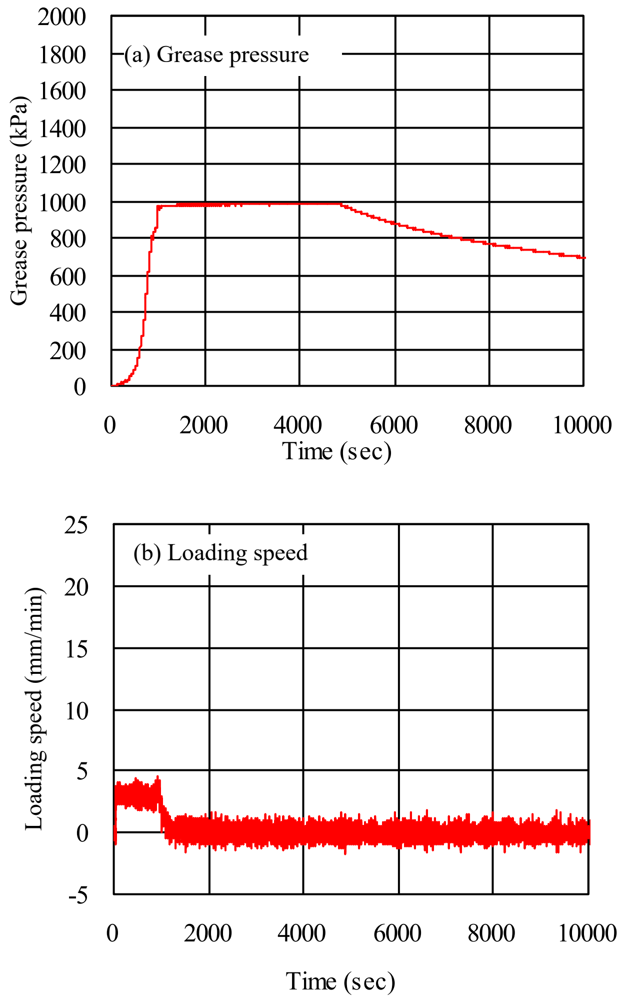


Figure 18 Elapsed time vs. grease p. and loading speed (T_C70mm WBL, M3)

5. CONCLUSIONS

This research carried out the element tests to examine the water-sealing performance by the proposed method, which is to reduce work atmospheric pressure in a working chamber at the bottom of pneumatic caisson for one hour. Furthermore, the influence of some properties on water-sealing performance and its mechanism were discussed. As a result, the following were made clear:

1. To ensure high water-sealing performance, the WB needs the function to increase the contact force of WB to excavation surface and the contact length of WB with excavation surface so that the WB can fit excavation surface well, and to reduce the gap between the inner surface plate and the excavation surface and the open space at a slit.
2. The σ_{gmax} is smaller, as the height of roughness is higher, the width of roughness is narrower, and the tail clearance is larger.
3. The following type wire brush can ensure high water-sealing performance: 1) the WB with the stiff surface plate with slits and the flexible and strong protection cloth, compared with the WB with the stiff surface plate with slits only; and 2) the longer surface plate, since they can reduce the gap between the inner surface plate and the excavation surface and the open space at a slit.
4. Not only the displacement control method but also the stress control method was used in this study, considering the application in practice. It was confirmed that the grease supply for water-sealing can be saved by the stress control method, when the water-sealing performance of WB is high.
5. In the case of the improved wire brush, WBL, the following were confirmed: 1) the maximum grease pressure σ_{gmax} reaches 1.5 MPa and 1.0 MPa by the displacement control method and the stress control method, respectively; 2) the residual rate of grease pressure after one hour from grease supply stop is more than 75%; and 3) the WBL has enough water-sealing performance.

Here, the height of steel bar, which simulates the height of the roughness of excavation surface, is only 20 mm. Therefore, to ensure the reliability of this method, the following are necessary as a future research: 1) the improvement on the shape and the component of WB to increase the allowable height of the roughness of excavation surface; and 2) the investigation on the control method of excavation to increase the flatness of excavation surface.

6. ACKNOWLEDGEMENT

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