Development of Sliding Foundation Structure using Graphite Friction Material

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Abstract

In recent years, in Japan much damage is occurring due to major earthquakes such as the 1995 Great Hanshin Earthquake and the 2011 Great East Japan Earthquake. Concerning these earthquakes, ground motion acceleration of a magnitude that is far greater than the earthquake motion assumed in the current building standards law is observed. However, the only performance requirement stipulated by the current building standards law is the ability to prevent loss of human life resulting from the collapse of a building. Damage to a building and also demolishing of a building subsequent to a disaster are permitted. On the other hand, as methods of realizing aseismic performance that enable a building to continue to be used after a large earthquake, a seismic isolation structure and also a seismic control structure have been commercialized. However, in the case of a small to medium scale building, these structures have not come into sufficiently wide spread due to high cost and other factors.

Accordingly, the authors developed and practicalized a "Sliding Foundation Structure (hereafter called a sliding foundation)" which uses graphite as the friction material [1]-[6]. A sliding foundation is a composed of a reinforced concrete slab (foundation slab) installed on an artificial ground made of concrete. The surface of this artificial ground is coated with graphite powder that has a small coefficient of friction. When the ground acceleration during an earthquake reaches a constant value, the static friction between the artificial ground and the foundation plate (sliding surface) is lost, causing the foundation slab to slide, and thus reduce the response on the building (Fig.1). The Sliding foundation has high seismic performance similar to isolation structure. Also, low cost and can be constructed easily.

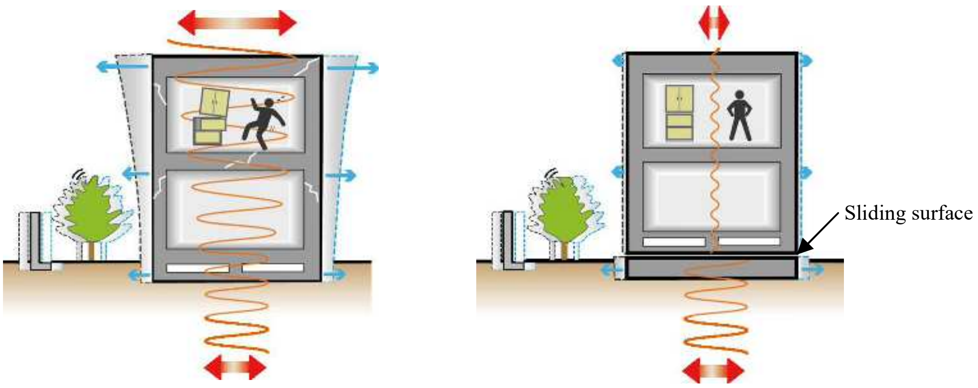
This paper describes an outline of a sliding foundation and also its seismic performance, together with examples of experiments and analyses. The main contents are as follows.

1) The friction coefficient of the sliding surface is stable at approximately 0.15, and the input acceleration to the foundation slab peaks out approximately 150cm/sec^2 even under the maximum ground motion acceleration of 600cm/sec^2.

2) By providing a gentle ascending taper on the outer periphery of the surface of the artificial ground, the issue of the one-sided flow phenomenon was solved, enabling the residual displacement to be suppressed.

3) The actual workability and sliding performance were checked by the 8m×8m full-size test.

Keywords: Sliding foundation, Graphite, Input reduction, Isolation effect



(a) Fix foundation building (b) Sliding foundation building

Fig.1 – Comparsion between a fixed foundation and a sliding foundation in a large earthquake

1. Introduction

This paper describes the outline and the seismic performance of the sliding foundation structure using graphite as a friction material. Chapter 2 covers the composition of the sliding foundation structure [1],[2]. Chapter 3 shows the effects of applying the sliding foundation structure from experimental and analytical results [2],[3]. Chapter 4 shows that the one-sided flow phenomena and the residual displacement, which are issues of the sliding foundation structure, have been solved by providing a gentle uphill slope from the center to the outer periphery on the upper surface of the artificial ground [3]-[6]. Chapter 5 shows the workability was confirmed through the production of a full-scale test specimen assuming a typical RC detached house in Japan. In addition, an experiment conducted to confirm the performance of a full-scale sliding foundation structure is described [3]. Chapter 6 is a summary of this paper.

2. Composition of Sliding Foundation Structure

Fig.2 shows the composition of the sliding foundation structure, which consists of the ① foundation slab, ② PC slab, ③ graphite (friction material), and ④ artificial ground made of concrete. It does not require special equipment. By applying a friction material with a low coefficient of friction to the artificial ground, when the acceleration of the artificial ground reaches a certain value due to a large earthquake, the friction disappears and the foundation slab integrated with the PC slab slides on the artificial ground. This structure causes the horizontal force applied to the building to decrease [1],[2].

Photo 1 shows the friction material (graphite) and the sliding face. For the friction material, graphite having a friction coefficient of approximately 0.15 is used. When concrete slabs that are not coated with graphite are used, the friction coefficient of the contacting faces is a large value of about 0.7, making the slabs difficult to slide. However, in the case of a sliding foundation that uses graphite, the friction coefficient is reduced to approximately 0.15, enabling the foundation slabs to slide easily. Graphite is a material which is generally used in the fields of machinery as a solid lubricant. It features low cost and also has excellent lubricating performance, durability and heat resistance.

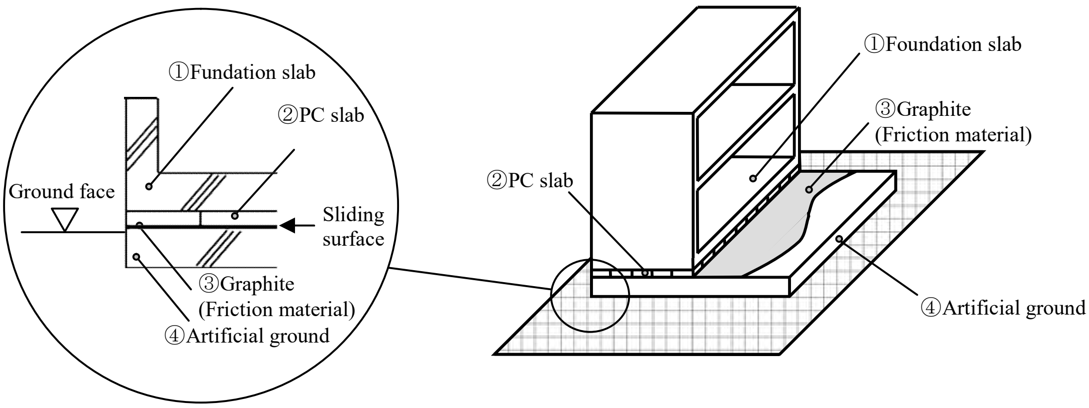


Fig.2 – Configuration of sliding foundation structure

Photo 1 – Friction material (graphite) and sliding faces

3. Application Effect of Sliding Foundation Structure

Fig.3 shows a comparison between a general fixed foundation and a sliding foundation when an earthquake occurs. Fig.4 shows the behavior of the foundation slab of the sliding foundation structure when a large earthquake occurs. Regarding a sliding foundation, when the ground acceleration exceeds a certain value, the foundation slab slides over the artificial ground, causing the acceleration input to the building foundation to peak out. As result of the input reduction effect to the building foundation, compared to a fixed foundation the response acceleration that occurs on the building is reduced. Therefore, damage to the frame of the building can be avoided and also a secondary disaster caused by toppling of furniture, for example, can be prevented.

This chapter shows a shaking test to the sliding foundation structure which confirmed the input reduction effect and the dependence of the friction coefficient [2],[3]. Further, an example of response analysis in which the response reduction effect of the building is confirmed will be described [3].

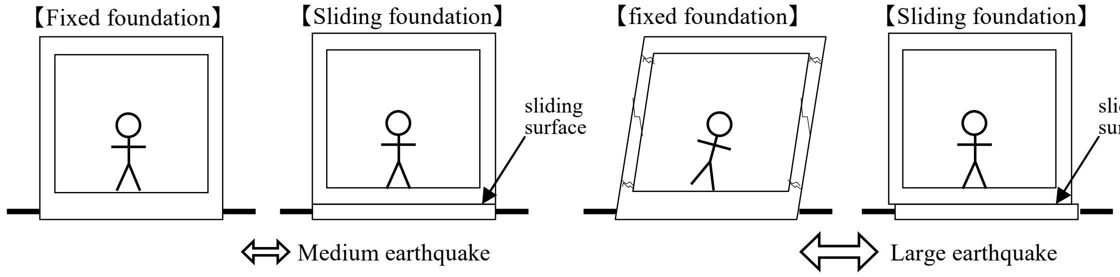


Fig.3 – Behavior when an earthquake occurs

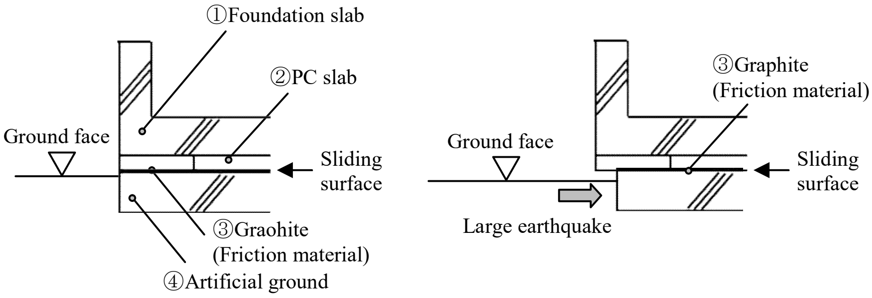


Fig.4 – Behavior of foundation when a large earthquake occurs

3.1 Confirmation of Input Reduction Effect - Shaking Test -

Table 1 shows an outline of the test body, and Table 2 shows the input waveform. Also, Photo 2 shows the test situation. In this test, a sliding foundation test body consisting of a 1.5m × 1.5m concrete artificial ground and a foundation slab was fabricated, and the artificial ground was fixed to the shaking table on which was installed an actuator. A non-stationary wave and a stationary wave set so that the maximum acceleration was about 600cm/sec^2 were used.

Table 1 – Outline of test

Name	Dimension(m)	Weight(kN)
Artificial ground	1.5×1.5×0.2	10
Foundation slab		

Table 2 – Input waves

Input wave	Max Disp. (cm)	Max Vel. (cm/sec)	Max Acc. (cm/sec^2)
Stationary	3.8	48	600
Non-stationary	14	65	710

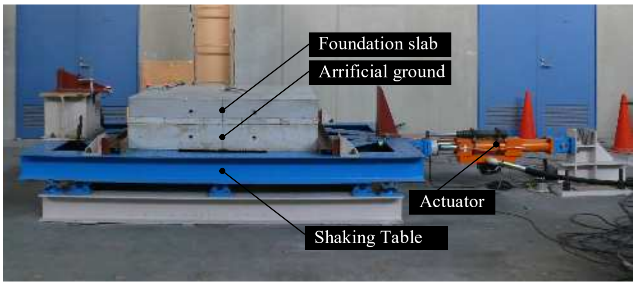
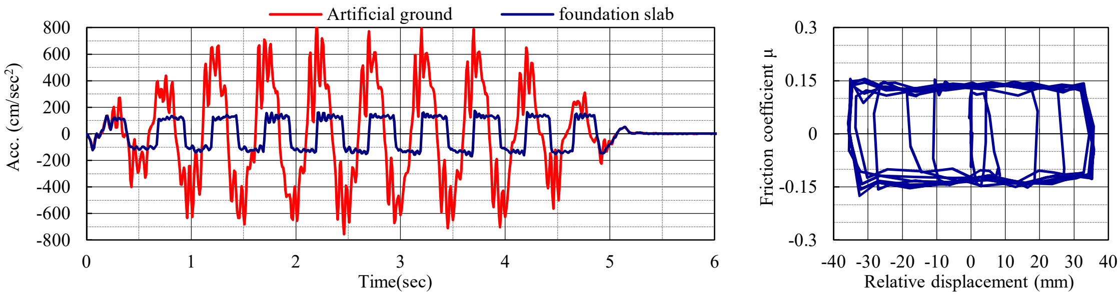


Photo 2 – Test situation

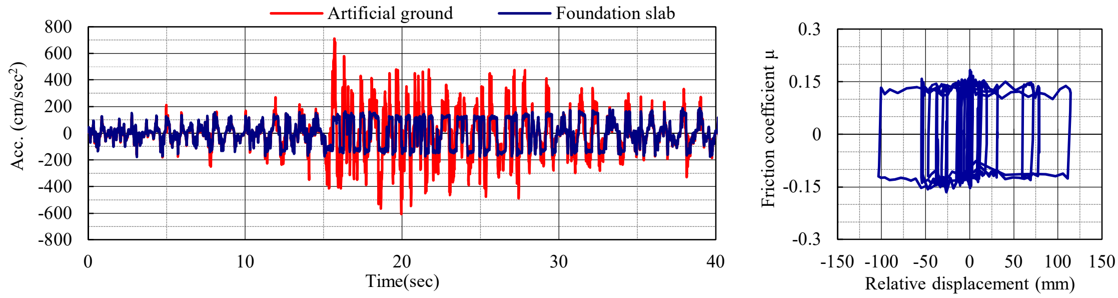
Fig.5 shows the results of applying stationary waves, and Fig.6 shows the results of applying non-stationary waves. The friction coefficient shown in (b) of each figure was calculated by dividing the acceleration generated at the foundation slab by the acceleration due to gravity (g = 980cm/sec^2). The relative displacement was calculated from the difference between the absolute displacement of the artificial ground and the absolute displacement of the foundation slab.

From (a) "the acceleration time history waveform" in each figure, it can be seen than the maximum acceleration generated at the foundation slab peaks out at approximately 150cm/sec^2, thus demonstrating the input reduction effect of the sliding foundation structure. Also, from (b) "the relationship between the friction coefficient and the relative displacement," it can be seen that, regardless of whether the input wave is a stationary wave or a non-stationary wave, the friction coefficient of graphite (friction material) is a constant value of approximately 0.15, this indicating stable sliding performance.



(a) Acceleration time history wave (b) Friction coefficient – Relative displacement

Fig.5 – Results of stationary wave



(a) Acceleration time history wave (b) Friction coefficient – Relative displacement

Fig.6 – Results of non-stationary wave

3.2 Various Dependences on Friction Coefficient

Apart from the 2 waves shown in subchapter 3.1, shaking tests covering 11 cases were performed. The specifications of the input wave are shown in Table 3 and Table 4. These results were used as shown below to indicate the various dependencies on the friction coefficient.

Table 3 – Input waves (stationary wave)

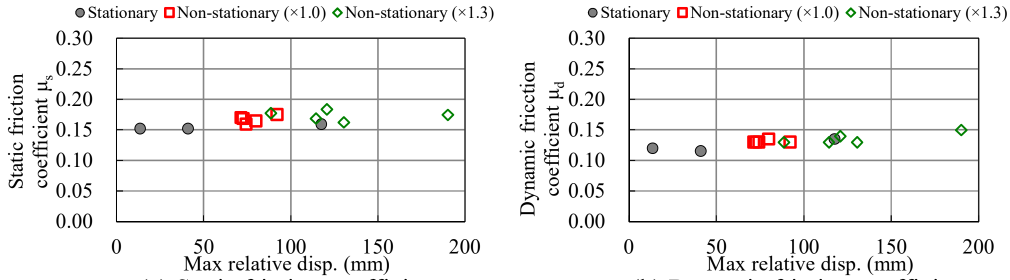
Wave name	Waveform	Nomber of cycles	Frequency	Max Amp. (cm)	Max Vel. (cm/sec)	Max Acc. (cm/sec^2)
1.33Hz85mm	Sine wave	Total of 10 including a gradual increase/decrease	1.33	85	71	594
2Hz38mm			2	38	48	600
4Hz9.5mm			4	9.5	24	600

Table 4 – Input waves(non-stationary wave)

	El Centro-NS		Taft-EW		Hachinohe-EW		Kobe-NS		Random	
	×1.0	×1.3	×1.0	×1.3	×1.0	×1.3	×1.0	×1.3	×1.0	×1.3
Disp. (cm)	8	10	9	12	10	13	11	15	9	12
Vel. (cm/sec)	44	57	40	53	51	67	54	70	46	59
Acc. (cm/sec^2)	535	695	634	824	550	715	511	665	507	660

1) Displacement dependency

Fig.7 shows the relationship between the friction coefficient and the maximum relative displacement. From this figure, it can be seen that for various stationary and non-stationary waves of maximum relative displacement between 13.5 and 190.2mm, the static friction coefficient exceeds 0.15 in all cases. Also, the dynamic friction coefficient has stabilized in the range of 0.12 to 0.15 in all cases. From the above, the displacement dependency cannot be confirmed for friction coefficient.

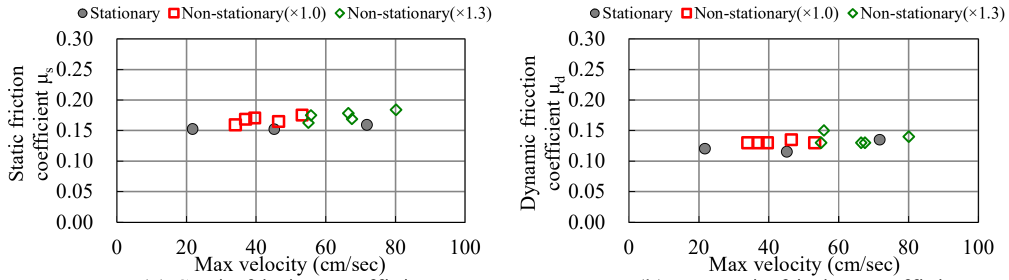


(a) Static friction coefficient (b) Dynamic friction coefficient

Fig.7 – Relationship between the friction coefficient and the maximum relative displacement

2) Velocity dependence

Fig.8 shows the relationship between the friction coefficient and the maximum velocity. From this figure, it can be seen that for various stationary and non-stationary waves between the maximum velocities of 21.8 to 80.2cm/sec, the static friction coefficient exceeds 0.15 in all cases. Also, the dynamic friction coefficient has stabilized within the range of 0.12 to 0.15 in all cases. From the above, the displacement dependency cannot be confirmed for friction coefficient.



(a) Static friction coefficient (b) Dynamic friction coefficient

Fig.8 – Relationship between the friction coefficient and the maximum relative displacement

3) Repetitive durability

Fig.9 shows the relationship between the dynamic friction coefficient and the cumulative sliding amount corresponding to 3 stationary waves. It indicates the transition of the friction coefficient when 3 stationary waves are applied intermittently every 10 cycles, to 1 test body. The horizontal axis indicates the cumulative amount, and the vertical axis indicates the dynamic friction coefficient for each cycle. From the figure, it can be seen that the dynamic friction coefficient remains almost unchanged even when the total sliding displacement that occurs reaches about 3700mm. In all cases, the friction coefficient has stabilized over the range from 0.11 to 0.15. From the above, the sliding foundation has excellent repetitive durability.

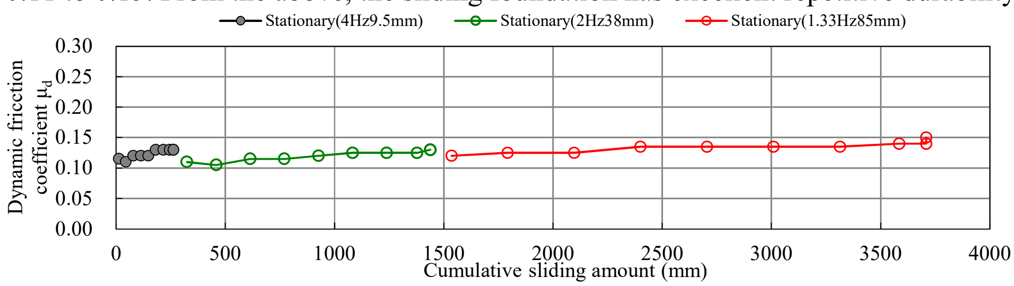
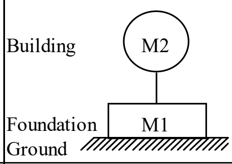
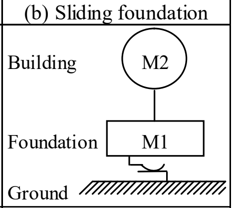


Fig.9 – Relationship between the dynamic friction coefficient and the cumulative sliding amount

3.3 Confirmation of Response Reduction Effect - Response Analysis -

Table 5 shows an analysis model, and Fig.10 shows the input earthquake characteristics. For the analysis model, 2 models, a fixed foundation model and a sliding foundation model were set. In both models, the mass ratio between the foundation (M1) and the building (M2) was set to be 1: 1. The natural period (T) of the building is T = 0.75sec. Also, in the sliding foundation model, to enable the foundation slab to slide when the friction coefficient μ is 0.15, the complete elastoplastic spring that yields under a force equal to 15% of the total building weight was set between the foundation slab and ground. The input earthquake motion was defined as a non-stationary wave that has the spectral characteristics shown in Fig.10.

Table 5 – Analysis model

		(a) Fixed foundation	(b) Sliding foundation
Analisys model			
Foundation	History characteristics	-	Elastic-perfectly plastic
	Furiction coefficient	-	0.15
Building	Natural frequency	0.75esc	
	Damping	5% (stiffness proportional type)	

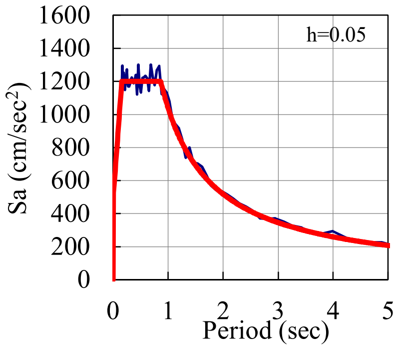
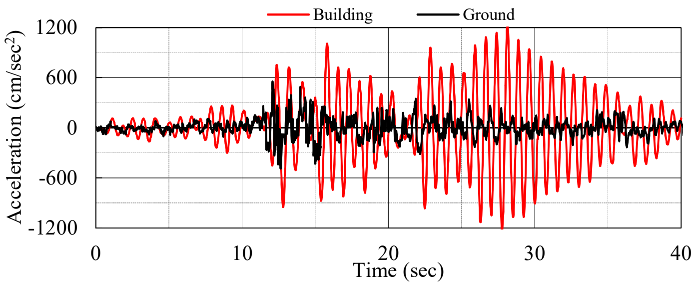


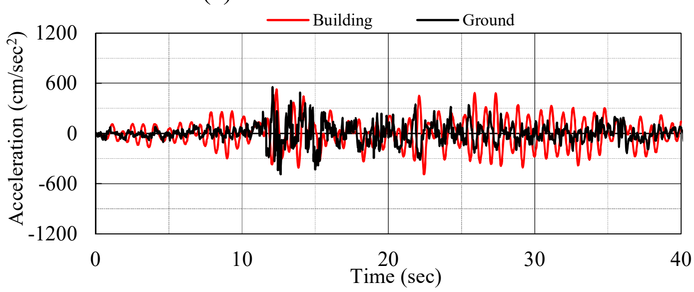
Fig.10 – Input earthquake

Fig.11 shows the acceleration time history waveform of the ground and a building, obtained from the response analysis. Concerning (a) “the fixed model,” the response acceleration of the building has increased to more than twice the ground acceleration, and the maximum response acceleration has reached 1200cm/sec^2. In contrast, concerning (b) “the sliding foundation model,” the maximum response acceleration of the building is about 600cm/sec^2, and it can be seen that it has fallen to about 50% compared to the fixed foundation model.

Note that, the same result can be obtained by changing any of the natural period (T = 0.25 to 0.75sec), the mass ratio between the foundation and the building (M1:M2=1:0.33 to 1:3), and the input waveform.



(a) Fixed foundation model



(b) Sliding foundation model

Fig.11 – Response analysis results

4. Sliding Foundation Structure with Taper

Regarding a sliding foundation structure, in the event of a major earthquake, sliding will occur between the artificial ground and the foundation slab. As a result, whereas the artificial ground undergoes a large displacement, the absolute displacement of the foundation slab decreases. However, regarding the sliding foundation structure which does not have any recovery ability, there is a possibility that after an earthquake occurs, a residual displacement may occur between the artificial ground and the foundation slab. For this reason, as shown in Fig.12, it was decided to provide a gentle ascending taper on the upper face of the artificial ground, going from the center part and facing the outer periphery, and thereby create a structure that could suppress the residual displacement. By doing this, it is possible to solve the issue of the one-sided flow phenomenon moving to one side each time sliding occurs during an earthquake. Also, by deliberately providing a taper, it is possible to solve the issue of construction error on the surface of the artificial ground.

This chapter describes a shaking test which has confirmed the sliding performance of a tapered sliding foundation structure [3]-[6].

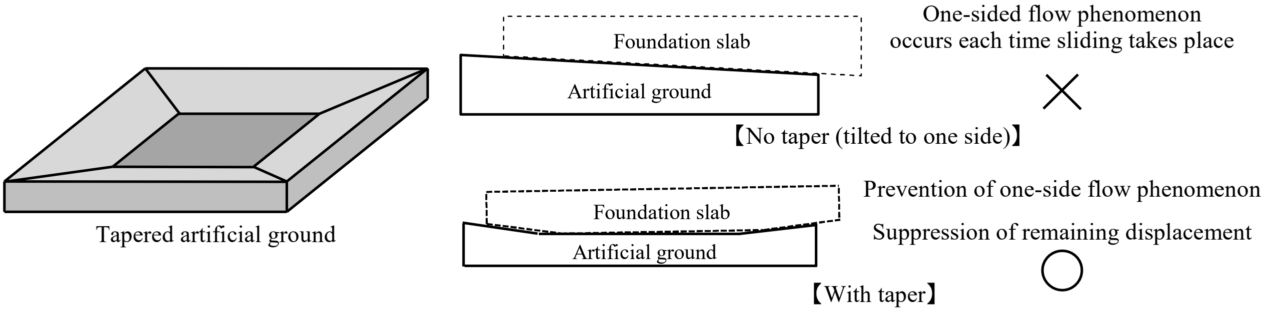


Fig.12 – Concept of artificial ground with taper

4.1 Confirmation of Taper Effect - Shaking Test -

Fig.13 shows the test body. The size of the foundation slab was set to 1.8m × 1.8m. The height difference of the taper that was provided in the direction facing the outer periphery from the center part was set to 3 values: 0, 5, 15 mm. The test method used was a shaking test. The input consisted of 1 stationary wave and 1 non-stationary wave, the maximum acceleration of both is about 600cm/sec^2.

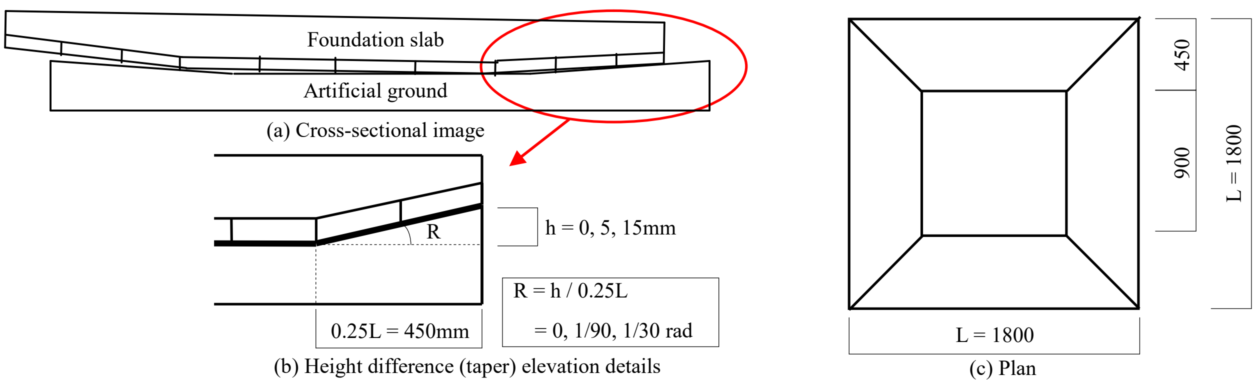
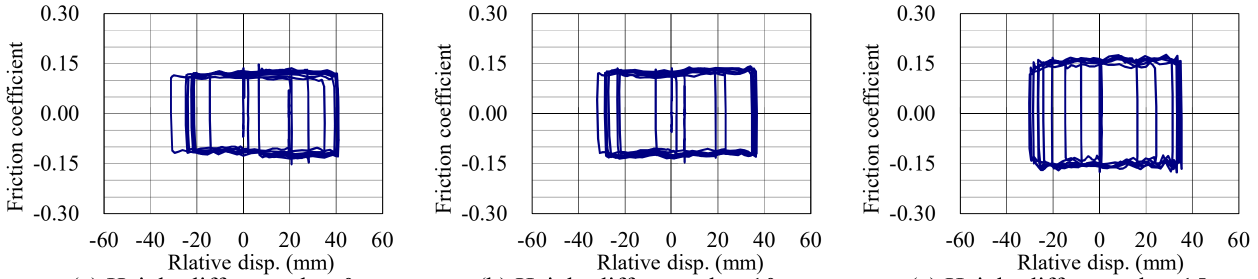


Fig.13 – Test body (with taper)

Fig.14 shows the relationship between the friction coefficient and the relative displacement acquired from the test. From this figure, it can be seen that the friction coefficient is constant, regardless of the height difference and the input waveform, thus indicating stable sliding performance.

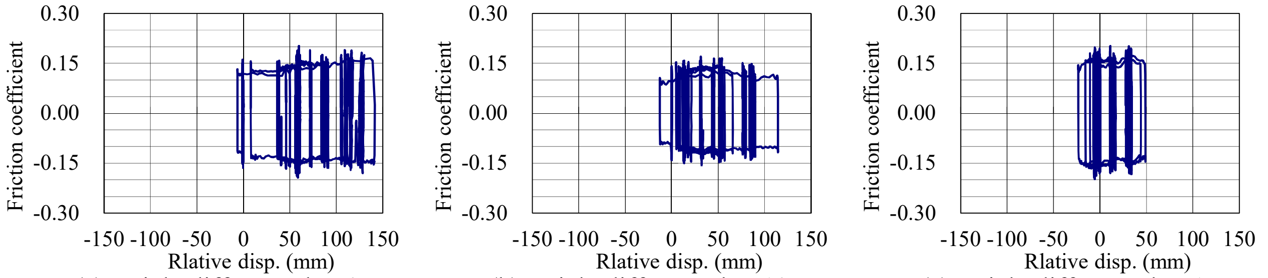
Fig.15 shows the time history waveform of the relative displacement. From this figure, it can be seen that when there is no height difference (h = 0mm), a one-sided flow phenomenon in which the foundation slab moves to one side each time sliding takes place occurs, but that this phenomenon can be suppressed by applying a height difference.

Fig.16 shows the relationship between the height difference h and the dynamic friction coefficient, the maximum relative displacement and the residual displacement. From (a), it can be seen that when the height difference h is 15mm, there is a tendency for the dynamic friction coefficient to be somewhat large. However, the effect of the height difference on the dynamic friction coefficient is small, and it can be seen that the sliding performance is stable. Also, from (b) and (c), it can be seen that the application of a height difference is effective in suppressing maximum relative displacement and also residual displacement.



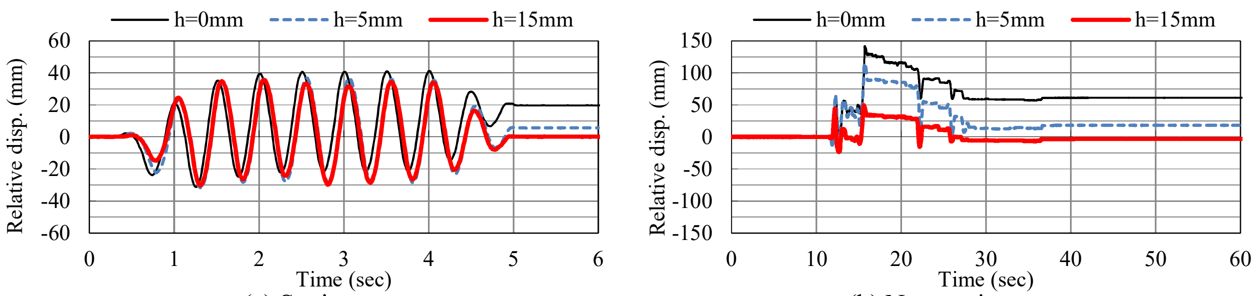
(a) Height difference h = 0 mm (b) Height difference h = 10 mm (c) Height difference h = 15 mm

Fig.14 (i) – Relationship between friction coefficient and relative displacement (stationary wave)



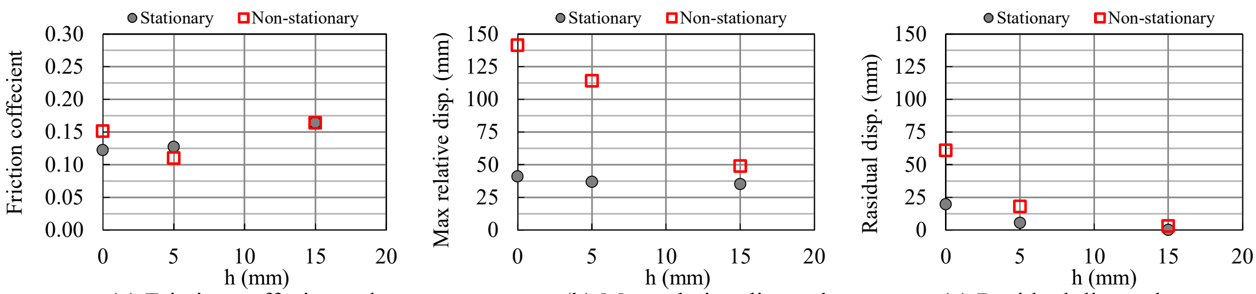
(a) Height difference h = 0 mm (b) Height difference h = 10 mm (c) Height difference h = 15 mm

Fig.14 (ii) – Relationship between friction coefficient and relative displacement (non-stationary wave)



(a) Stationary wave (b) Non-stationary wave

Figure 15 – Relative displacement time history waveform



(a) Friction coffecient – h (b) Max relative disp. – h (c) Rasidual disp. – h

Figure 16 – Relationship between the height difference and the friction coefficient, max relative disp. , and residual disp.

5. Construction Experiment and Sliding Performance in Full Size

One of the issues that remain concerning the realization of a sliding foundation structure is the confirmation of the workability by using a full-size test body, and confirmation of the sliding performance. Concerning these issues, a full-size validation test was performed using a full-size (planar dimensions: 8m × 8m) test body. This size assumes a detached house made of RC, which is common in Japan.

This chapter describes the actual situation of full-size construction and the sliding performance of full-size [3].

5.1 Construction Experiment in Full Size

Fig.17 shows the procedure for constructing a sliding foundation, and Photo 3 shows the construction situation.

The full-size test body has planar dimensions of 8m ×8m and a height of 0.65m (artificial ground height: 0.25m, foundation slab thickness: 0.35m). After the concrete for the artificial ground had cured, the surface of the artificial ground was polished, and then coated with 1.9kg (30g/m^2) of graphite. This was covered completely by laying 0.3m × 0.3m PC slabs on it, and then the foundation concrete was cast over these PC slabs to prevent the foundation concrete from adhering to the sliding face. Note that the PC slabs have been chamfered to prevent the corners from become chipped.

The actual construction was completed satisfactorily without any need for special equipment or skills. During the construction, it was particularly necessary to control the height difference on the artificial ground. It is difficult to realize an error of ±0mm in the height of the 8m × 8m artificial ground over its entire surface. For the reason, the control value of the height of the top end of the concrete was made 0+4mm, and the control value of the center part was made 0-4mm, thus enabling construction of a sliding foundation that can prevent one-sided flow, as in the case of the tapered test body mentioned in Chapter 4.

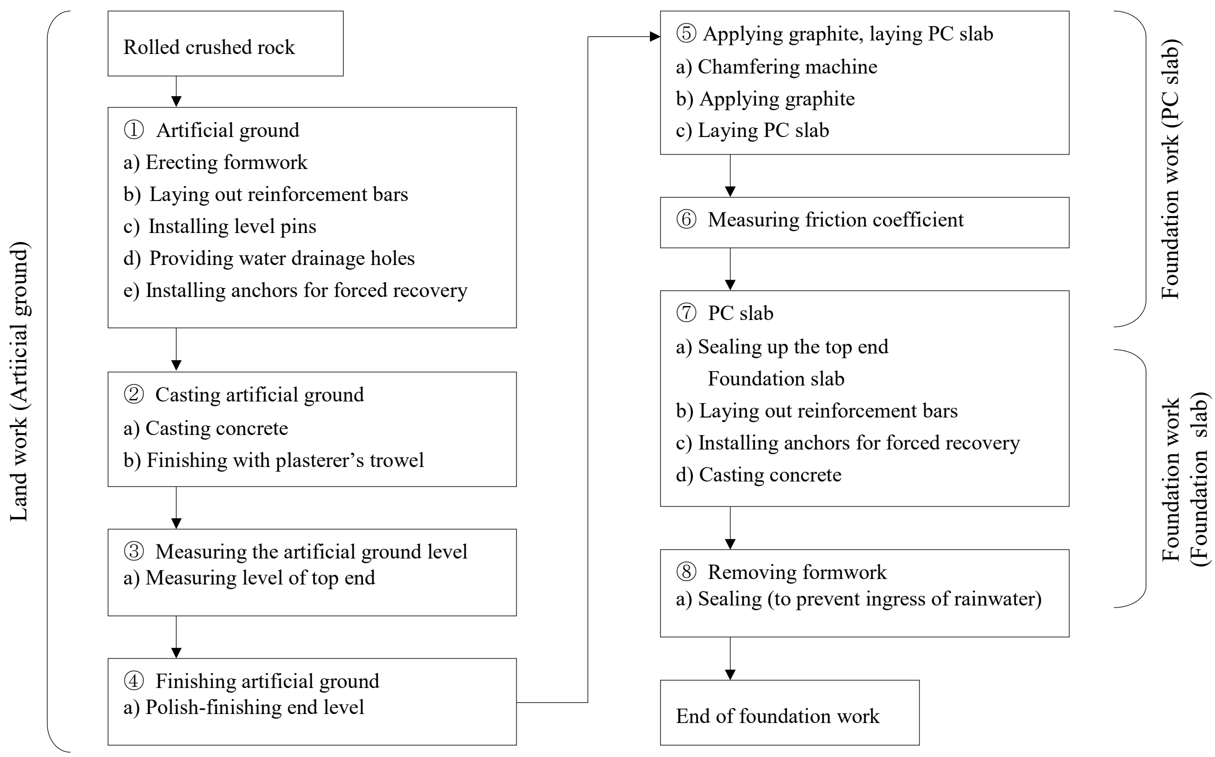


Fig.17 – Work procedure

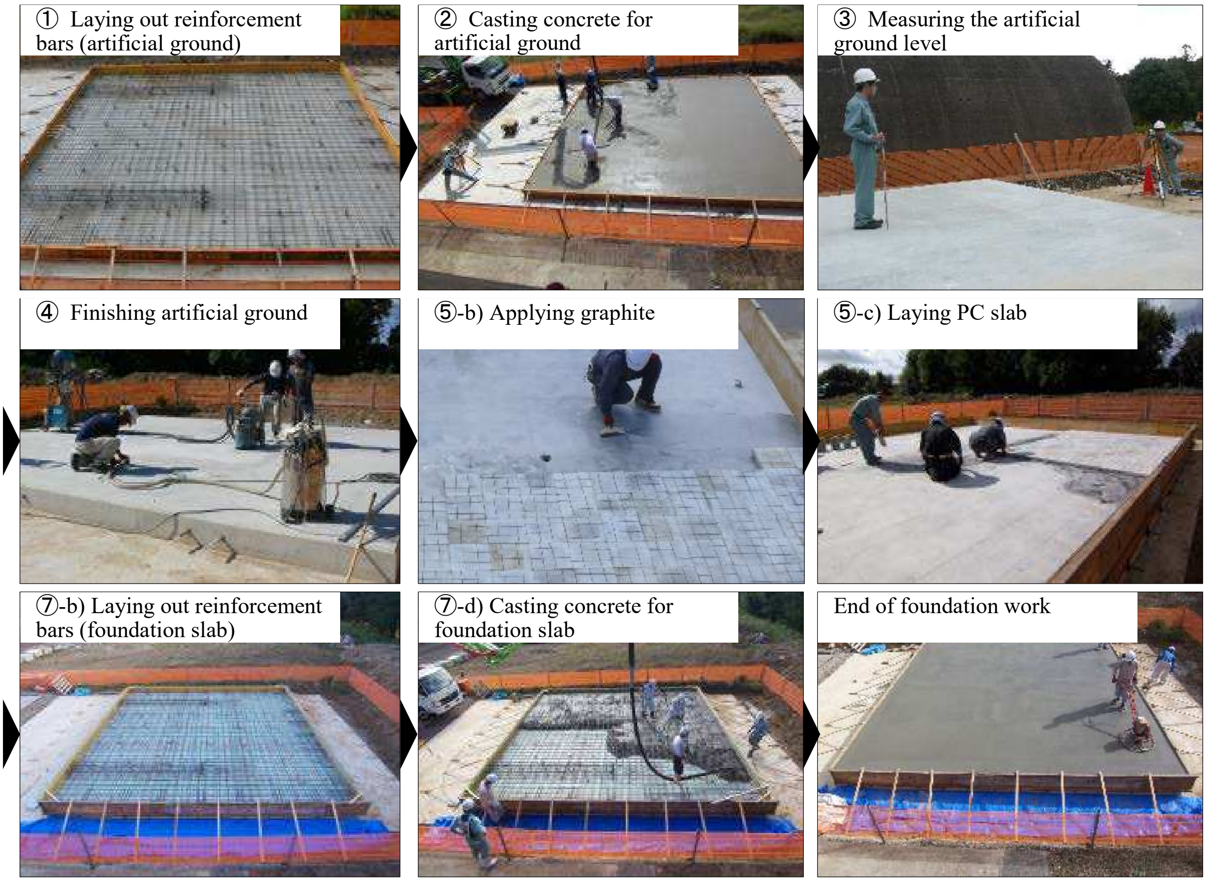


Photo 3 – Construct situation of full-size

5.2 Sliding Performance in Full Size

Fig.18 shows the situation regarding the mounting of the test body, and Photo 4 shows the situation of the test. The stress application test involved installing a reaction jig at the site (outdoors) where the full-size test was to be performed, on the side face of the artificial ground, and then directly pushing and pulling the foundation slab by means of 2 hydraulic jacks. Also, 3 water tanks were installed on the foundation slab and the amount of water was adjusted, enabling a weight corresponding to a 1- to 2-story detached house to be reproduced.

Table 6 shows the test parameters. In order to confirm the dependency of the sliding performance on the face pressure in this test, the amount of water was adjusted. As a result, the weight to be reproduced is changed in 4 steps (665kN, 910kN, 1155kN, 1400kN). Here, "building weight" is the total weight of the foundation slab and the tanks containing water. The face pressure is the value obtained by dividing the building weight by the plane area (8m × 8m = 64m^2). Note that the total weight of the 3 water tanks when empty is 127kN (standard value), and the water volume is calculated from the measured water level. The stress application was 2-cycles at amplitude of ±200mm, and the velocity was assumed to be about 1.0cm/sec. The measurement items used were horizontal force (sliding resistance force of the foundation slab) and the relative displacement (between the artificial ground and the foundation slab). The measurement method uses a load cell mounted on the end of each hydraulic jack, and the relative displacement uses a wind-up type displacement gauge.

Fig.19 shows the relationship between the horizontal force obtained from the stress application test and the relative displacement, and also between the friction coefficient and the relative displacement. The friction coefficient shown in (b) was calculated by dividing the horizontal force measured using the load cell by the building weight shown in Table 6.

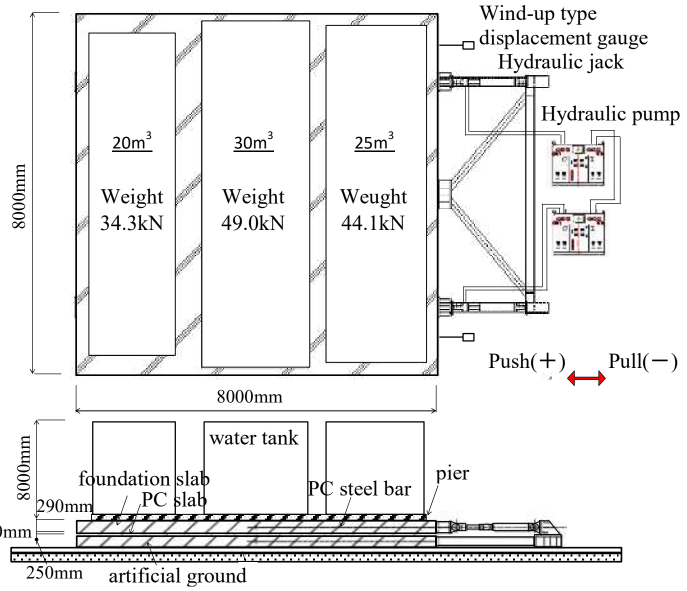


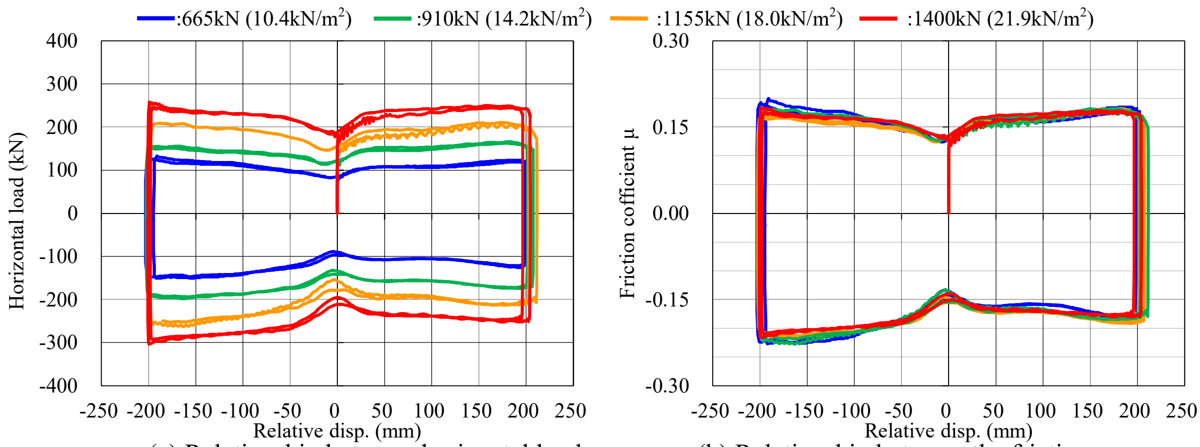
Fig.18 – Test body installation situation

Photo 4 – Test implementation situation

Table 6 – Test parameter

Case	Building weight (kN)	Face pressure (kN/m^2)	Weught ratio
1	665	10.4	1.00
2	910	14.3	1.38
3	1155	18.0	1.73
4	1400	21.9	2.11

From (a) "relationship between horizontal load and relative displacement," the horizontal load near the point where relative displacement is 0mm is somewhat small, however it can be seen that sliding will take place under a stable horizontal load. Also, from (b) "relationship between the friction coefficient and the relative displacement," even if the building weight is changed, the friction coefficient will remain unchanged, and will be stable within the range of 0.15 to 0.2. It can therefore be said that the dependency of the face pressure on the friction coefficient is small. The friction coefficient (μ = 0.15 to 0.2) obtained in the full-size test is almost the same as the coefficient of friction obtained in the test using the reduced specimen described in Chapters 3 and 4. It can therefore be said that the friction coefficient is not dependent upon the area of the sliding face either.



(a) Relationship between horizontal load and relative displacement

(b) Relationship between the friction coefficient and relative displacement

Fig.19 – Results of stress application test using full-size test body

6. Conclusion

This paper describes the sliding foundation structure using graphite as a friction material.

1) Chapter 2 describes the composition of the sliding foundation structure. It indicates that the structure is simple and that there is no need for special equipment.
2) Chapter 3 describes the application effect of using a sliding foundation. The friction coefficient of the sliding surface is stable at approximately 0.15, and the input acceleration to the foundation slab peaks out approximately 150cm/sec^2 even under the maximum ground motion acceleration of 600cm/sec^2.
3) Chapter 4 describes the sliding performance of a tapered sliding foundation structure. By tapering the upper face of the artificial ground, the one-sided flow phenomenon and the residual displacement, which were issues concerning the sliding foundation structure, were solved. This chapter also indicates that even if the artificial ground is tapered, it exhibits stable sliding performance.
4) Chapter 5 describes the full-size validation test which assumes a general RC detached house which is common in Japan. It indicates that, even if a full-size test is performed, it is easy to carry out the construction, and also stable sliding performance can be realized.

7. Acknowledgements

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8. References

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