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FRICTION COEFFICIENT FOR EXPOSED COLUMN BASE DESIGN

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ABSTRACT :

In the standard base plate connection in steel structures, namely the exposed column base, the shear force is resisted by the combination of anchor bolt shear and friction between the steel base plate and mortal, which is placed just underneath the plate for the purpose of alignment. For the column base design, a static friction coefficient of 0.5 is commonly used. This value, however, was obtained from old test results, and furthermore there is no theoretical justification for the friction mechanism between steel and mortal. This study examines these problems by a series of static tests and dynamic tests. Tests were conducted, with the steel surface and the axial load as the test variables. The test results show that the initial static friction coefficient for steel and mortal is about 0.5, and gradually rises up to 0.8. After that, the coefficient remains very stable regardless of the slip distance.

KEYWORDS: Friction Coefficient; Exposed Column Base; Shaking Table Test

1. INTRODUCTION

Exposed column bases are widely used for low-rise buildings in Japan. They resist shear force by the combination of the anchor bolt shear and the friction between the steel base plate and the mortar placed under the base plate to make the column horizontal. For the column base design code in Japan (2006), a static friction coefficient of 0.5 is commonly used. This value, however, was obtained from a series of experimental results of 40 years ago by Washio et al. (1969) and Sei (1977). It was not enough to consider the cyclic friction behavior, the theoretical justification for the friction mechanism, and dependency on the friction conditions (Tanaka 1985). Moreover in the column base design, the behavior and friction strength during slip were rarely considered.

On the other hand, while the static friction coefficient between steel components with mil-scale is 0.2 – 0.35, the static friction coefficient between steel and mortar is 0.5. This means that the static friction coefficient between hard materials is smaller than that between soft material and hard material. From a series of studies, it is known that the dynamic coefficient is different for the static coefficient, and that even the static coefficient has dependencies on the velocity, the vertical force, and other factors (Uno et al. 1997, Nagae et al. 2006).

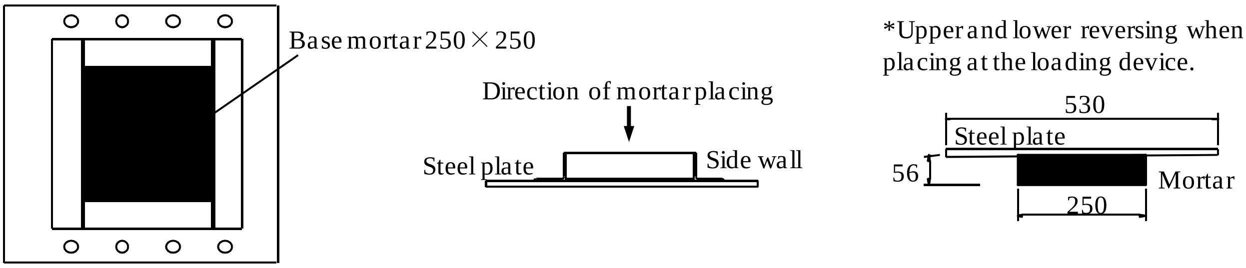
This study considers these problems through a series of static tests and dynamic tests. For the static tests, we considered the friction surface conditions, the vertical force at the friction surface, and cyclic friction slip behavior. For the dynamic test, we considered the dynamic friction coefficient and the dynamic friction slip behavior.

2. STATIC FRICTION TEST

2.1. Static Test Setup

Figure 1 shows the test specimen. The base mortar has a square surface (250mm×250mm×56mm). The mortar is placed directly on the steel plate with a side wall to cure. When loading, this element is inverted so the mortar is on the bottom. As shown in Table 1, three friction surfaces are considered in the static test, (1) steel with mil-scale and mortar, (2) blast-processed steel (blast steel) and mortar, (3) steel with mil-scale and steel with mil-scale. The friction system between steel and mortar is considered in cases (1) and (2), and Case (3) tests traditional frictional behavior. In Case (3), a steel plate (250mm×250mm×60mm) is used instead of the mortar block. The contact conditions between steel and mortar may influence frictional behavior, so for Case (1), the mortar and steel are separated and again set the same position to compare with Case (2). In Case (2), the specimen is set without separation. Vertical force, in accordance with the axial force ratio of the boxed column, is considered to be 0.1, 0.2, and 0.3. This means that the applied vertical forces are 200kN, 400kN, and 600kN. For Cases (1) and (2), constant vertical force is applied for each force level and one variable force ranges from 200kN to 600kN. For Case (3), only a test for 400kN vertical force is conducted. Mortar used in this test is standard high-stress non-shrinking mortar for filling the steel base-plate and concrete base. From coupon test results, the compression stress is 51N/mm^2.

Figure 2 shows the loading device. The upper steel plate is connected to the vertical jack and the horizontal jack. The specimen bottom, that is, the mortar bottom, is fixed by the device to stop the slip. When the horizontal force is applied to the steel plate, slip occurs at the boundary between the steel and mortar (or, in case (3), steel and steel). In all test cases except for No. 4 and No. 8, vertical force is constant for each value. In No. 4 and No. 8, vertical force is 200kN when horizontal force is positive, and vertical force is 600kN when horizontal force is negative. Horizontal loading is controlled by the relative slip between steel and mortar. The slip amplitude targets are 6mm, 12mm, and 24mm for both positive and negative sides for each case. When the mortar specimen undergoes serious damage, such as large cracks, the test is terminated.



(a) Plan (with side wall) (b) Section (when mortar setup) (c) Section (when loading)

Figure 1 Specimen for steel and mortar (Unit: mm)

Table 1 Static test specimen

No.	Surface 1	Surface 2	Condition	Vertical force (kN)
1	Steel with mil-scale	Mortar	Once separating	200
2				400
3				600
4				200-600
5	Blast processed steel	Mortar	Sticking	200
6				400
7				600
8				200-600
9	Steel with mil-scale	Steel with mil-scale	Once separating	400

2.2. Static Test Result

Figure 3 shows the test result of No. 2 up to 6mm slip. When shear force reaches the static friction force and slip occurs, shear force decreases significantly and the relationship between shear force and slip becomes saw-shaped. This is called stick-slip and is considered to occur because of the stiffness of the specimen, the loading device, and in the low speed (the static test). When the maximum shear force is large, the loading frame stores the large stress energy, and the ratio of the force reduction becomes large. In the static test, we consider the shear force just before the slip, and we ignore the stick-slip behavior.

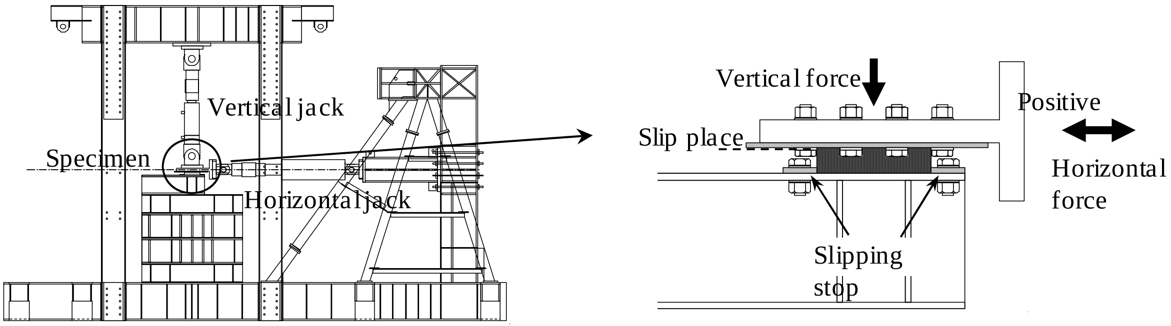


Figure 2 Specimen and test device

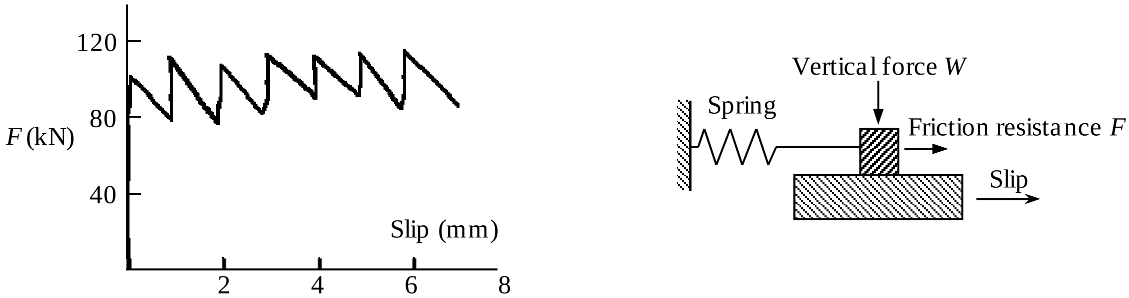
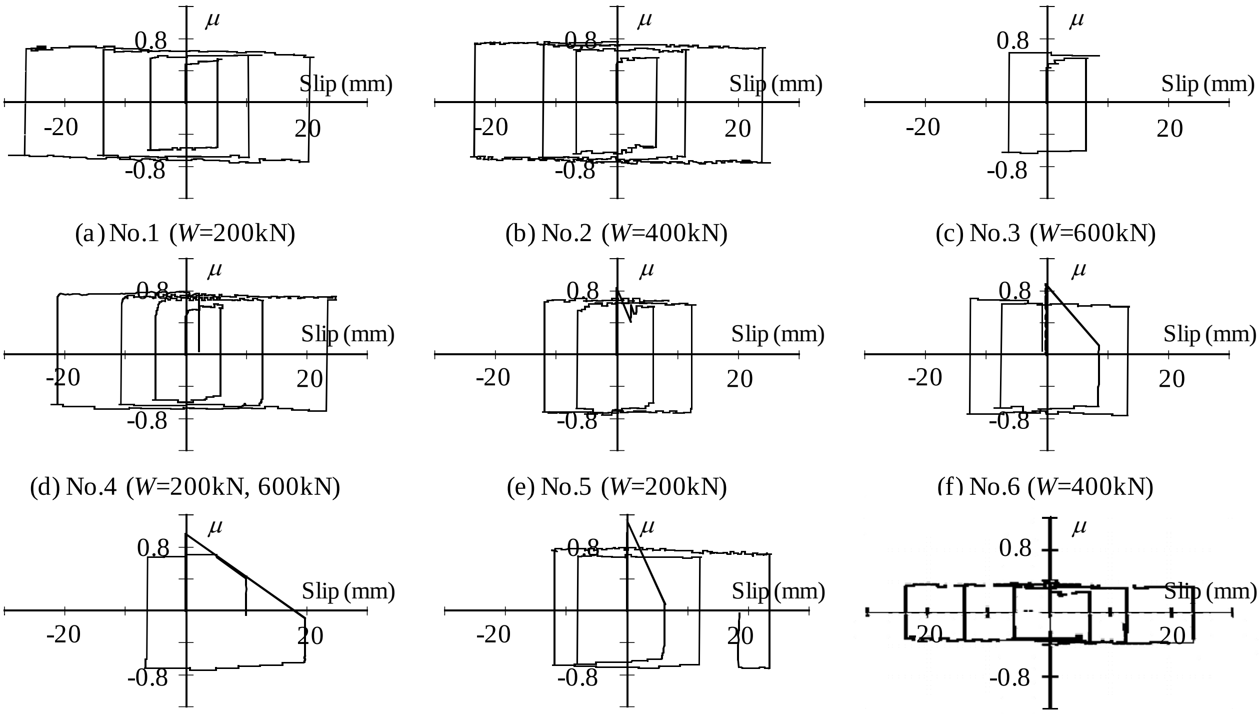


Figure 3 Stick-slip phenomena (test result and concept)



(a) No.1 (*W*=200kN) (b) No.2 (*W*=400kN) (c) No.3 (*W*=600kN)

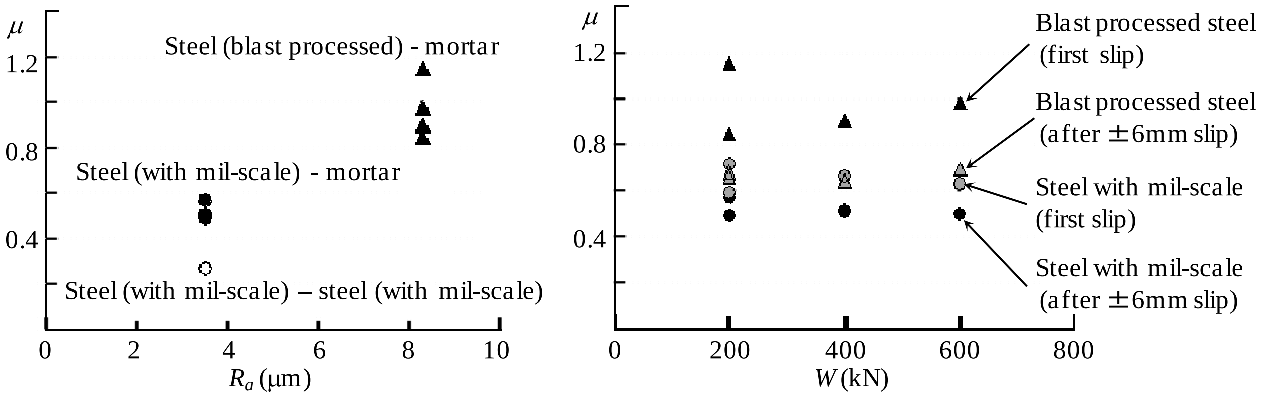
(d) No.4 (*W*=200kN, 600kN) (e) No.5 (*W*=200kN) (f) No.6 (*W*=400kN)

(g) No.7 (*W*=600kN) (h) No.8 (*W*=200kN, 600kN) (i) No.9 (*W*=400kN)

Figure 4 Static test result (Friction coefficient and slip relationship)

Figure 4 shows the relationship between the slip and friction coefficient, defined as the division of the horizontal force by the vertical force. In these figures, friction coefficient values just before the slip are accounted. Note that in No. 3, 5, 6, 7, and 8, loading was terminated before the predetermined loading amplitude

24mm. This is because a crack appeared at the mortar edge and the mortar could no longer resist the axial force. Figure 4(a), (b), (c), and (d) are the results of steel with mil-scale and mortar. For any axial force condition, the positive and negative static friction coefficients are almost symmetrical. Even for No. 4, in which the axial force is different for positive and negative direction, the static friction coefficient is symmetrical, so that the influence of the axial force on the static friction coefficient could not be observed. Figure 4(e), (f), (g), and (h) are the results from the blast-processed steel and mortar. The reduction of frictional force for the first slip is large, but after the first slip, behaviors for positive and negative side remain symmetrical regardless of the vertical force. Figure 4(i) is the result of steel with mil-scale and steel with mil-scale. The frictional force for the first slip is small but soon increases, and the friction coefficient becomes symmetral. For all friction cases between steel and mortar, after several slips the static friction coefficient reaches around 0.7 to 0.8.



(a) Roughness – Friction coefficient (b) Vertical force – Friction coefficient

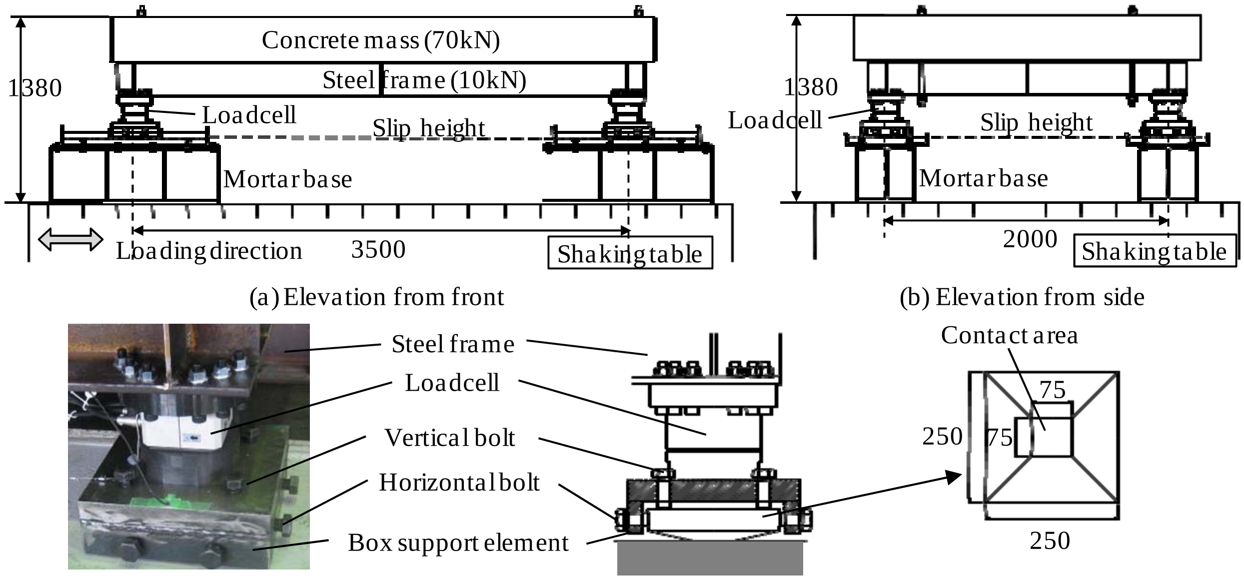
Figure 5 Friction coefficient at the first slip

To see the friction coefficient dependency for the surface conditions, a ten-point average roughness Ra was used. This value is measured by the needle touch method, and shows the average value of mountain heights averaged from highest to the 5th highest value and smallest to the 5th smallest value. The result shows that Ra for steel with mil-scale is 3.5μm, and Ra for blast-processed steel is 8.3μm. Figure 5(a) shows the relationship between static coefficient and Ra. The static coefficient of steel and steel with mil-scale is 0.27, while the average static coefficient of steel with mil-scale and mortar is 0.52. The static coefficient of blast-processed steel and mortar is 0.97, 1.9 times larger than that of steel with mil-scale and mortar. This means when that the surface materials are the same, the higher roughness makes the friction coefficient higher, but when the materials are different, even equal roughness results in different friction coefficients. Figure 5(b) shows the relationship between the static coefficient and the vertical force. This figure shows the initial static coefficient and static coefficient after a 6mm slip. In all cases except for the initial slip, for blast-processed steel the static coefficient is constant for any vertical force. Thus it seems that the vertical force does not affect the static coefficient. The value varies widely for the static friction coefficient between the blast-processed steel and mortar, but the relation with the vertical force was not notable. The effects of cyclic loading can be checked from the relationship between coefficient (black plot) at the first slip friction and the static coefficient after the 6mm slip (gray plot). Comparing the two average values, in the case of friction between steel with mil-scale and mortar (circle plot), the friction coefficient becomes larger up to 1.3 times at the ±6mm slip, but in the case of blast-processed steel and mortar, the coefficient becomes smaller by up to 0.7 times. After the first slip, the friction coefficient between blast-processed steel and mortar becomes almost the same as that between steel with mil-scale and mortar.

3. DYNAMIC FRICTION TEST

3.1. Dynamic Test Setup

Figure 6 shows the specimen for the dynamic test. The specimen is assumed to be the column system for steel building, and consists of three elements: mortar base, column base, and upper structure. The concrete base in this study is simulated by the mortar on the wide flange. The mortar base is rigidly fixed to the shaking table by bolts. The mortar size is 550mm×1020mm, and when the column base is set at the center of the base maximum slip is 300mm. The mortar is reinforced by deformed bar D13 to avoid the tensile yielding. Mortar compression stress is 35N/mm^2, from the coupon test. The column base consists of the steel column base-plate element and three-directional loadcell which is placed to measure the shear force and axial force directly. Considering the mass of the upper structure and the column stress ratio, the column base-plate element area is 75mm×75mm. This element is part of the support element. Horizontal and vertical bolts at the support element transmit the shear force and the vertical force for each column base. The loadcell is connects rigidly to the support element by bolts. Before loading, the monitored vertical force for four column bases is adjusted by the vertical bolt at the support element. The upper structure consists of a concrete mass and a steel frame. The steel frame is supported by the column base system at the four edges. The top of the loadcell and steel frame bottom are connected by bolts. The concrete mass and the steel frame are connected by the anchor bolts. Mortar stress is 14.6N/mm^2.



(a) Elevation from front (b) Elevation from side
(c) Column base part (d) Column base part section (e) Baseplate element

Figure 6 Dynamic test specimen

Figure 7 shows the picture of the specimen and the shaking table. Immediately after placing the mortar, the mortar surface is flattened with the steel plate with mil-scale. Then, before the setup on the shaking table, the steel plate is removed and the flat surface for the mortar is obtained. The shaking table with six degrees of freedom is 5m x 3m in size, and maximum acceleration and velocity is 1.0g and 1.5m/s for each direction.


(a) After mortar placing (b) Shaking table with mortar base (c) Shaking table with whole specimen

Figure 7 Specimen photograph

Table 2 shows the loading cases. All input waves are sine wave, and loading time is ten seconds. In this study, only horizontal input waves are adapted. Parameters are frequency and amplitude. For frequency, 1Hz, 2Hz, and 5Hz are considered, while for amplitude from 6m/s^2 to 10m/s^2. Vertical force and horizontal force for each column base are measured by the loadcell at the column base. To quantify the slip, relative displacement between column base and mortar are measured.

Table 2 Dynamic test loading cases

		Amplitude					
		6m/s^2	7m/s^2	8m/s^2	9m/s^2	10m/s^2	11m/s^2
Frequency	1Hz	1Hz-6m/s^2	1Hz-7m/s^2	1Hz-8m/s^2	1Hz-9m/s^2	-	-
	2Hz	2Hz-6m/s^2	2Hz-7m/s^2	2Hz-8m/s^2	2Hz-9m/s^2	2Hz-10m/s^2	2Hz-11m/s^2
	5Hz	5Hz-6m/s^2	5Hz-7m/s^2	5Hz-8m/s^2	5Hz-9m/s^2	-	-

3.2. Dynamic Test Result

Figure 8 shows the behavior of slip and friction coefficient. Slip is defined as the average of 4 column bases slip. Friction coefficient is defined as the average value of the 4 column bases horizontal force divided by the vertical force. The slip does not occur when amplitude is 6m/s^2.when amplitude is larger than 7m/s^2, in all cases slip occurs. Slip value is significantly different according to the input wave. Two types of slip behavior are notable, one from same frequency vibration as the input wave and another from drift slip toward one side. Also the slip velocity depends on the input wave, but the difference of friction behavior by the slip velocity is not observed. The maximum slip velocity is 0.28m/s when the input wave is 2Hz-11m/s^2. Both static and dynamic friction coefficient are almost same for all cases to 10 seconds, so the behavior is elast-plastic.

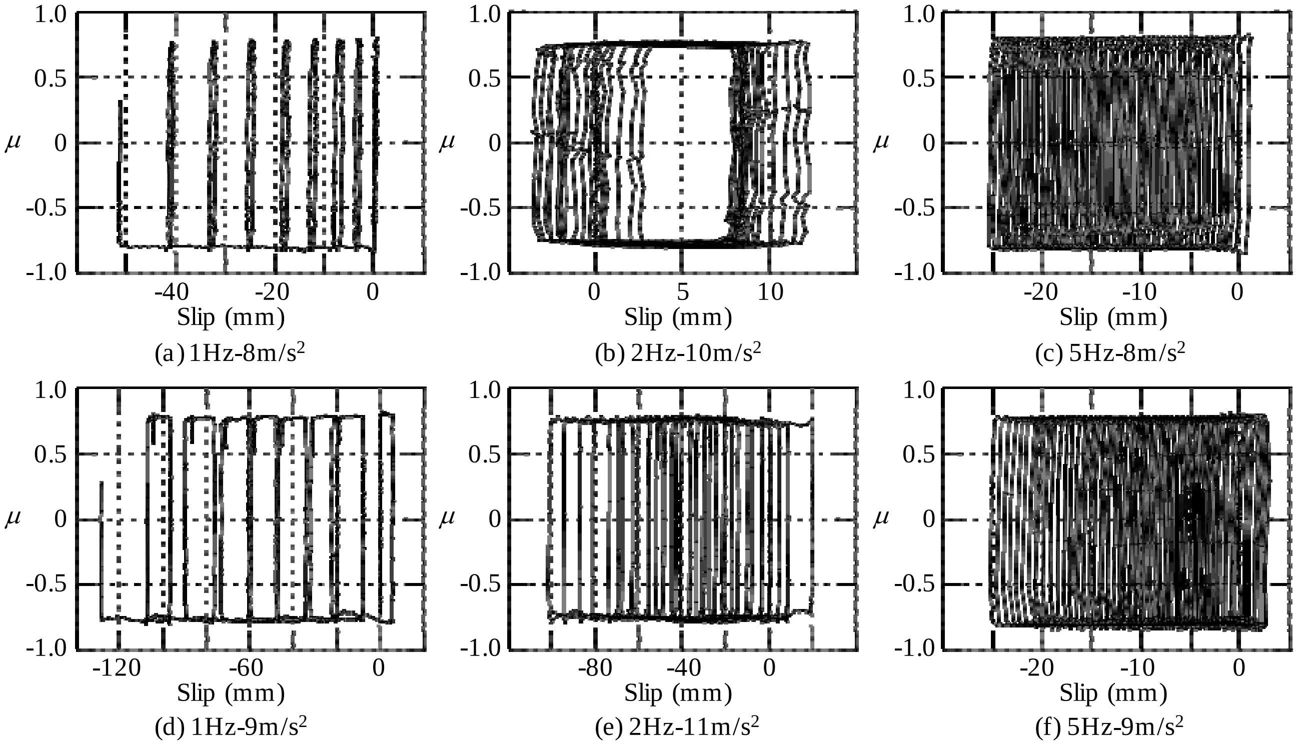


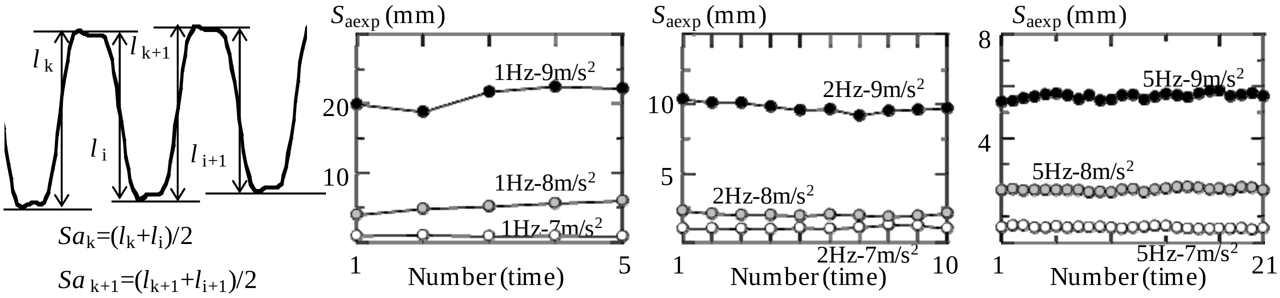
Figure 8 Dynamic test result (Friction coefficient and slip relationship)

Table 4 shows the average value of static friction coefficient for all cycles. The static and dynamic friction coefficient is same. The values of this table represent both the static and dynamic friction coefficient. The value is from 0.74 to 0.83, and average is 0.78, which is almost 1.4 times larger than the value of Japanese design code and same as the static test result. The value is very stable regardless of the input wave and slip direction.

To know the slip behavior detail, the average slip between the positive peak and negative peak for one cycle (equivalent slip) is considered. Figure 9 shows the relationship between slip number and equivalent slip. For each case, the equivalent slip is very stable regardless of the slip times. The equivalent slip grows with the increase of the maximum acceleration amplitude. Also when the input wave frequency becomes large, the slip becomes large.

Table 4 Dynamic test result (Static friction coefficient)

Frequency	1Hz		2Hz		5Hz	
Amplitude	Positive	Negative	Positive	Negative	Positive	Negative
$7m/s^2$	0.74	0.78	0.76	0.76	0.8	0.83
$8m/s^2$	0.76	0.8	0.77	0.77	0.8	0.82
$9m/s^2$	0.76	0.77	0.76	0.76	0.78	0.81
$10m/s^2$	-	-	0.74	0.78	-	-
$11m/s^2$	-	-	0.77	0.75	-	-
Average	0.78					



(a) Concept (b) 1Hz (c) 2Hz (d) 5Hz

Figure 9 Equivalent slip result

3.3. Dynamic Test Analysis

From the dynamic test result, the rigid plastic behavior is obtained for the slip behavior. Here, we consider the friction behavior from the dynamic analysis for a one degree of freedom model, and compare the analysis result with the corresponding test result. In the analysis, the static friction force is calculated from the static friction coefficient obtained from the test and specimen mass. The test result shows that the input waves have some different peak accelerations for the positive and negative loading. In the analysis, ideal sine wave and measured wave measured in the test are used to compare the difference. The static coefficient also has a small difference between positive and negative.

	Input wave	Static friction coefficient
a	Ideal sin wave	+0.78, -0.78
b	Measured wave	+0.78, -0.78
c	Measured wave	+0.76, -0.77

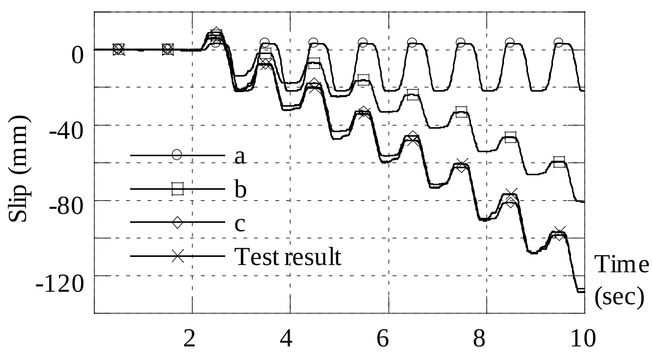


Figure 10 Time history analysis result

Figure 10 shows the analysis cases and results. For the ideal sine wave and same static friction coefficient for positive and negative direction, the slip never goes to one side. For the measured wave, the slip drifts to negative side because of the amplitude difference. And when the measured wave and different coefficient are used, the slip behavior is the same as that observed in the test. From this result, it becomes clear that the slip drift tendency depends on the input wave and static friction coefficient and slip behavior is very sensitive for the value of static friction coefficient.

4. CONCLUSION

To examine the basic friction behavior between steel and mortar, static and dynamic tests are conducted. From the static test, the basic friction behavior is obtained. The results are as follows. (1) The static friction coefficient between the steel and mortar is first 0.5 and it becomes around 0.8 during accumulative slip. (2) The condition of the friction surface affects significantly the friction coefficient. By the blast processed steel, the first friction coefficient becomes very large, but after first slip the friction coefficient decrease to 0.8, which is same as the value with steel with mil-scale. (3) The friction coefficient depends on the material surface roughness, but is independent of the vertical force in this study range.

From the dynamic test, the dynamic behavior during the slip is obtained. The results are as follows. (1) The dynamic friction coefficient between steel and mortar is same as the static friction coefficient. The coefficient is almost 0.8, which is same as the static test result. (2) Friction coefficient is very stable for the cyclic slip and has little relationship with the input wave. (3) The dynamic behavior can be simulated by the simple time history analysis of one DOF system.

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