

Experimental study on the shear behavior of the interface between cushion materials and the concrete raft

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Abstract: Cushion is a layer of granular materials between the raft and the ground. The shear behavior of the interface between the cushion and the raft may influence the seismic performance of the superstructure. In order to quantify such influences, horizontal shear tests on the interfaces between different cushion materials and concrete raft under monotonic and cyclic loading were carried out. The vertical pressure P_v , material type and cushion thickness h_c were taken as variables. Conclusions include: 1) under monotonic loading, P_v is the most significant factor; the shear resistance P_{hmax} increases as P_v increases, but the normalized factor of resistance μ_n has an opposite tendency; 2) for the materials used in this study, μ_n varies from 0.40 to 0.70, the interface friction angle δ_s varies from 20° to 35°, while u_{max} varies from 3 mm to 15 mm; 3) under cyclic loading, the interface behavior can be abstracted as a “three-segment” back-bone curve, the main parameters include μ_n , the displacement u_1 and stiffness K_1 of the elastic stage, the displacement u_2 and stiffness K_2 of the plastic stage; 4) by observation and statistical analysis, the significance of different factors, together with values of K_1 , K_2 and μ_n have been obtained.

Keywords: cushion/raft interface; shear behavior; monotonic test; cyclic test; “three-segment” back-bone curve

1 Introduction

Pile-raft foundation is a combination of a raft foundation and a pile foundation, where a large amount of piles are installed in the ground and rigidly connected to a thick raft. Meanwhile, the Non-Connected Pile-Raft Foundation (NCPRF) is different from the traditional pile-raft foundation for there exists a cushion layer with a thickness of 200–500 mm between the pile top and the raft bottom, as shown in Fig. 1. The cushion is made up of granular materials, which are usually crushed stone, sand or a grading mixture of them. Hence the cushion is deformable and maintains continuous contact with piles, soil and raft foundation at all times, which enables the soil to fully settle and results in the sufficient use of the capacity of the soil between piles.

In general, with the same configuration of piles, the NCPRF has the advantage of higher bearing capacity, smaller construction difficulty and lower cost compared with the traditional pile-raft foundation. As such, the NCPRF becomes more and more popular to be used in tall buildings (Wong *et al.*, 2000).

Other than the efficiency of NCPRF in supporting the superstructure vertically, the shear behavior of the interface between the cushion and the raft has some influence on the performance of the soil-structure interaction under lateral loads. The main lateral loads that act on structures are wind load and seismic loads. In the designing stage, the former can be equivalently treated as static load under which the shear resistance of the cushion/raft interface rises. The latter case is a dynamic load, under which the shear of cushion and the sliding of the raft has the effect of energy dissipation and seismic absorption. In both cases, the shear behavior of the cushion/raft interface should be studied quantitatively to make better prediction of the performance of the soil-structure interaction system.

There already exist many researches on properties of the interface between continuum and granular materials under monotonic and cyclic loading. Some tests focused on sand-concrete interface (Desai *et al.*, 1985; Gao *et al.*, 2000; Qian, 2002; Zhou, 2006; Lashkari, 2013), other tests focused on sand-steel interface (Uesugi and

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Kishida, 1986a; Tejchman and Wu, 1995; Fakharian, 1996; Frost *et al.*, 2002; Frost *et al.*, 2004; Hu and Pu, 2004; Zhang and Zhang, 2006; Mortara *et al.*, 2007). However, materials and particle sizes in these tests were different from the cushion. The loading and boundary conditions were also different from those of the cushion/raft interface (Yang and Xue, 1999; Hu and Pu, 2001; Porcino *et al.*, 2003; Zhang and Zhang, 2004a; Lu *et al.*, 2006). On the basis of these test results, some constitutive models were developed. Desai and Nagaraj (1988) first modified the Ramberg-Osgood function to describe the interface behavior. Then, the theory of plasticity was used to develop more complicated models (Mortara *et al.*, 2002; Hu and Pu, 2004; Saberi *et al.*, 2016; Saberi *et al.*, 2017). The critical state mechanics and particle breakage were included in some models (Desai *et al.*, 2005; Liu *et al.*, 2006; Liu and Ling, 2008; Liu *et al.*, 2014). Nevertheless, for the same reasons mentioned above, these results and models cannot be used directly in the analysis of cushion/raft interface. Moreover, they are also too complicated to be used in practice. Wu *et al.* (2007) carried out shaking table test on a model non-connected pile group, but the superstructure was not taken into account. With a rigid block representing the superstructure, Zhao *et al.* (2005) carried out a shaking table test to evaluate the seismic isolation effect of the sand cushion, but the vertical load was far smaller than that of a typical building. The research methods used in these publications provide valuable references for the study of shear behavior of cushion/raft interface. However, the true knowledge will not be obtained unless the tests have been finished on the same interface as that in practical NCPRF system.

In this study, the pseudo static loading method was used to carry out monotonic and cyclic tests on the shear behavior of the cushion/raft interface. Based on existing knowledge and engineering practice, vertical pressure P_v , material type and thickness h_c of the cushion were changed as variables. Main test results include: the shear resistance, the hysteretic properties and the “three-segment” back-bone curve of the cushion/raft interface. Correlated results of the main parameters can be guidance for relevant research and future engineering practice.

2 Interface shear test plan

Instead of the usual way of element test to study the interface shear behavior, a scaled model test plan was adopted to better recur the practical conditions of the NCPRF. Placed between the thick raft and the semi-infinite ground, cushion is a rather thin layer of granular material which is in a similar state as the confined soil. Hence a large-scale concrete shear box was used as the container for cushion materials.

The main factors may be considered in the test include: the vertical pressure on the cushion, particle size, initial porosity and thickness of the cushion. In practice, the value of initial porosity of the cushion is more or less fixed by following the standard construction procedures. Hence the vertical pressure, particle size or material type and thickness of the cushion are the 3 main variables in designing the tests.

2.1 Testing facility

The testing system was designed according to the Chinese code of pseudo static experiment (GB 50152-2012). The installation and instructions of different parts of the testing facility are shown in Fig. 2. The front view of the overall testing facility and every component is shown in Fig. 3. The detailed information of the main instruments are listed as follows.

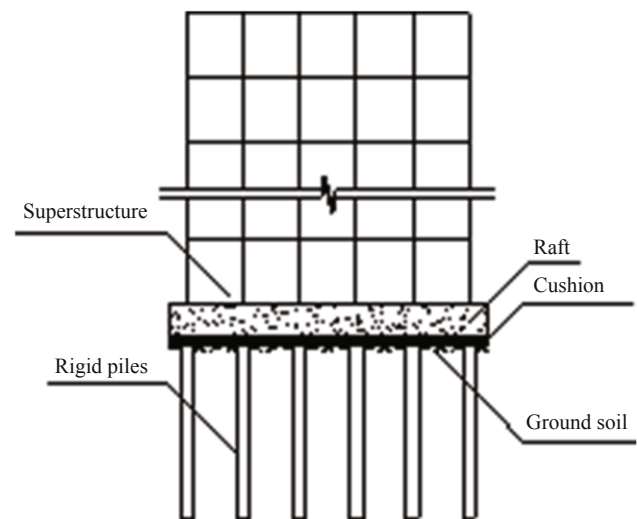
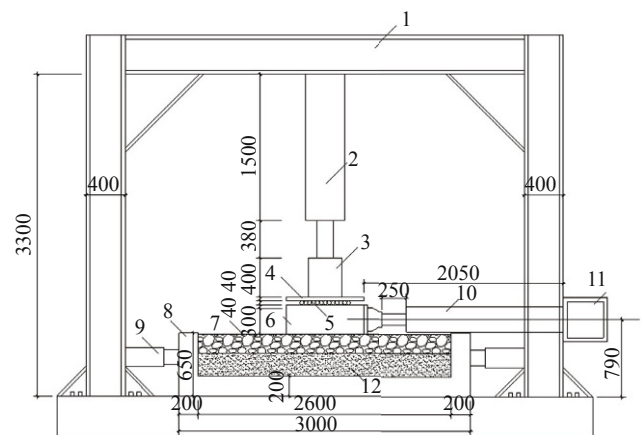


Fig. 1 The non-connected pile-raft foundation-superstructure system



Vertical view of loading facility 1:20 unit: m

1-Reaction frame; 2-Vertical jack; 3-Heel block; 4-40mm thick steel plate; 5-Roll shaft; 6-Rigid loading plate; 7-Cushion sample; 8-Shear box; 9-Support jacks; 10-Actuator; 11-Horizontal girder for instrumenting actuator; 12-Sand

Fig. 2 Schematic of the testing facility

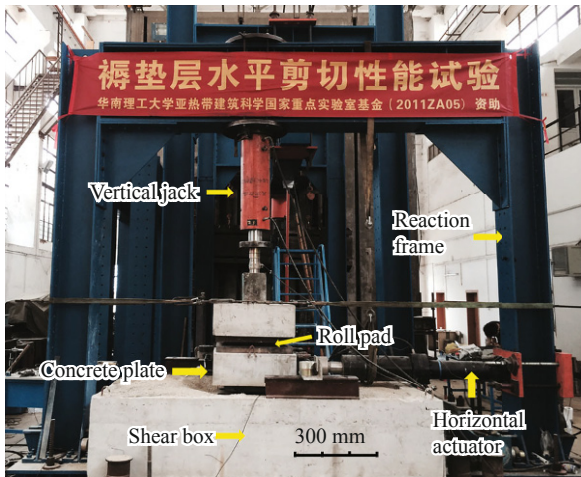


Fig. 3 Instrumented testing facility

The pre-cast concrete box for cushion has a dimension of 3000 mm × 1600 mm × 650 mm (length × width × height). The thickness of the side walls of the box is 200 mm. The dimension of the inner space is 2600 mm × 1200 mm × 450 mm. A 150 mm thick layer of sand was set at the bottom of the box as subsoil. Therefore the net depth inside the box is 300 mm, which is chosen as the maximum cushion thickness according to engineering practice.

The rigid loading plate, with a dimension of 800 mm × 600 mm × 300 mm (length × width × height), was pre-cast in concrete with a compressive strength of 40 MPa. A steel plate was pre-embedded into one side of the loading plate, which was used to connect the horizontal actuator. For the convenience of construction, the plain area of cushion is always larger than that of the raft. Meanwhile, the restrictions applied by the backfill is really limited in reality. Hence the plan dimensions of the plate was designed to be smaller than those of the shear box, such that the boundary conditions similar to that in the field conditions could be reproduced.

The horizontal force was applied by the actuator, which has a maximum loading range of 500 kN. The horizontal actuator was firmly connected to the loading plate at one end and the steel loading frame at the other. The horizontal reaction force was provided by the steel frame. The reaction force was estimated to be within 200 kN, which was less than the capacity of the steel frame.

The vertical pressure was applied by a hydraulic jack. To cover tall buildings with different height in the study, the vertical pressure in the tests varied in 6 grades: 100 kPa to 600 kPa with an increment of 100 kPa, which corresponded to 7, 13, 20, 27, 33 and 40 stories of buildings. The maximum force of the jack was 2500 kN, which was sufficient for the test. A roller pad was set between the vertical jack and the rigid loading plate, which was used to minimize the friction between the vertical jack and the loading plate when the plate moved horizontally.

2.2 Cushion materials

There are 3 types of materials commonly used in engineering practice: crushed limestone, river sand, and the mixture of crushed stone and sand (mixed with a volume ratio of 1:1). Hence these 3 types of cushion were selected for shear tests. The cushion is usually constructed using materials from the batching plant, hence the sand and crushed stone for the tests were purchased in one of these plants to best reproduce the engineering realities. The particle size distribution of the 3 materials are shown in Fig. 4. The tests were carried out with dry materials, whose physical parameters of these materials are listed in Table 1. Each material of cushion varied in the thickness of 100 mm, 200 mm and 300 mm.

2.3 Testing procedures

The testing procedures were programmed by following the Chinese code (GB 50152-2012) and referring to literatures of shear tests on granular/continuous material interfaces (Uesugi and Kishida, 1986b; Fakharian, 1996; Zhang and Zhang, 2004a and 2004b).

The monotonic loading tests were load-controlled. The horizontal force F was increased continuously by the actuator at a rate of 0.2 kN/s. The values of F were recorded from the operating platform of the loading system. The values of the horizontal displacement of the plate u were recorded by the mean reading of two dial indicators with a maximum range of 40 mm. The spring-loaded probes were set in touch with the front face of the plate in the loading direction. The base of the indicators was fixed at proper positions on the top of the two side walls. A separate data collector was used to record readings from the two dial indicators. At every increment of 5 kN of F , the readings of u were collected. Together with the corresponding horizontal force values, the F - u curves can be drawn. The loading had to be stopped at a point when u suddenly increased very fast, i.e. the moment when slide of the plate initiated, to protect the actuator and the dial indicators

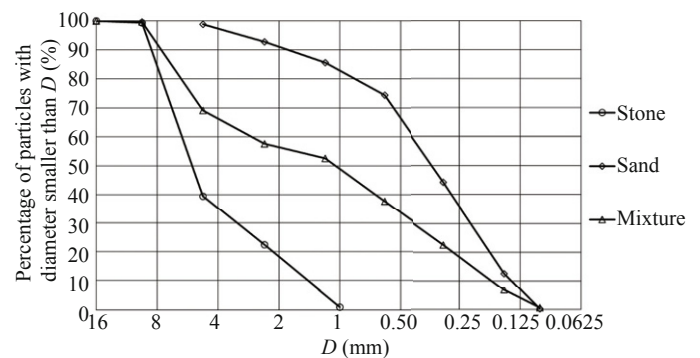


Fig. 4 Particle size distribution of cushion materials

Note: the abscissa is transferred by logarithm with a base of 2

Table 1 Density of different cushion materials

Material \ Property	Bulk density (kg/m ³)	Compacted density (kg/m ³)	Apparent particle density (kg/m ³)
Crushed stone	1450 (46%)	1640 (39%)	2670
Dry sand	1580 (40%)	1750 (33%)	2620
Stone-sand Mixture	1590 (40%)	1780 (33%)	2640

Note: The volume ratio is 1:1 for the mixture of crushed stone and dry sand. The percentage in parenthesis are the porosity corresponding to the densities.

from being broken in case of exceeding their ranges. Due to the vertical pressure and the movement of the concrete plate, the cushion need to be reconstituted when necessary. For monotonic loading, the loading facilities were removed after every two tests, i.e. after the vertical pressure of 200 kPa, 400 kPa and 600 kPa. Then the cushion materials were compacted and flattened using a vibrating plate. The volume of the cushion materials and the inner space of the shear box were fixed, hence the cushion/raft interface could be best reproduced to the original state after such compaction process.

The cyclic loading tests were displacement-controlled. The loading rate varied in 3 levels (0.1 mm/s, 0.2 mm/s and 0.3 mm/s) for different tests in order to study its effect on the interface shear properties. The plate was loaded continuously to a maximum value of $u = 40$ mm; then without break, it was loaded in the opposite direction to the negative minimum value of $u = -40$ mm. Test data were recorded by the readings of the actuator. By a trial test on the 300mm thick crushed stone cushion, it was proved that multiple force-displacement loops (3 cycles) almost match with each other under the same vertical pressure. Hence, the rest tests were stopped after one and a half loading cycles under different vertical pressure. Finally the F - u hysteretic loops can be drawn from the test results. Then the shear behaviors of the interface between commonly used cushion materials with different thickness and the concrete raft under different vertical pressure can be analyzed in detail.

There exists friction resistance between the roller pad and the loading plate. To guarantee the accuracy of the test results, additional tests were carried out under both monotonic and cyclic loading. In the calibration tests, another bottom roller pad was placed under the loading plate corresponding to the top roller pad. Then the plate was loaded following the same procedure as previous tests on the interface. Hence, the friction resistance between the roller pad and the loading plate can be obtained. The exact horizontal shear force can be calculated by deducting this part from the original results. The test results presented and discussed below have all been modified in the above-mentioned way.

3 Monotonic loading test

3.1 Test results and observation

The horizontal force-displacement (F - u) curves of different interfaces are drawn as Fig. 5 through Fig. 7. The left column of charts show the F - u curves of the same cushion/raft interface under different vertical pressures P_v , while the right line shows the F - u curves of the interfaces with different cushion thickness h_c but under the same vertical pressure. For the disturbance of the cushion after each test, the results under 200 kPa, 400 kPa and 600 kPa can not deliver true messages about the shear behavior of the interface. Hence the results have been eliminated from further analysis. The concrete plate started to slide when u suddenly increased rapidly while F stayed almost unchanged or slightly fluctuating. At this moment, the readings of force and displacement should be recorded as the interface shear resistance $F_{\max}$ and the shear displacement $u_{\max}$. All the curves have been terminated at the sliding points for better illustration.

To get the general rule, $F_{\max}$ can be transformed as shear resistance per unit of area $P_{h\max} = F_{\max}/A$, where A is the contact area. Then the normalized factor of shear resistance $\mu_n = P_{h\max}/P_v$ is calculated as listed in Table 2. The values of shear displacement $u_{\max}$ were shown in Table 3. From the test results, some important phenomenon and rules can be observed and summarized as follows:

(1) With the same cushion material and thickness h_c , the interface shear resistance per unit of area $P_{h\max}$ increases with the increase of vertical pressure P_v , so does the shear displacement $u_{\max}$. Nevertheless, the normalized factor of shear resistance μ_n decreases.

(2) With the same cushion material and P_v , both $P_{h\max}$ and μ_n fluctuate a little for different h_c , but with no particular rule. The cushion thickness seems to be insignificant for the variation of μ_n .

(3) With the same P_v and h_c , the $P_{h\max}$ (or μ_n) is the largest for crushed stone cushion, in majority cases, the $P_{h\max}$ (or μ_n) is larger for mixture cushion than sand cushion.

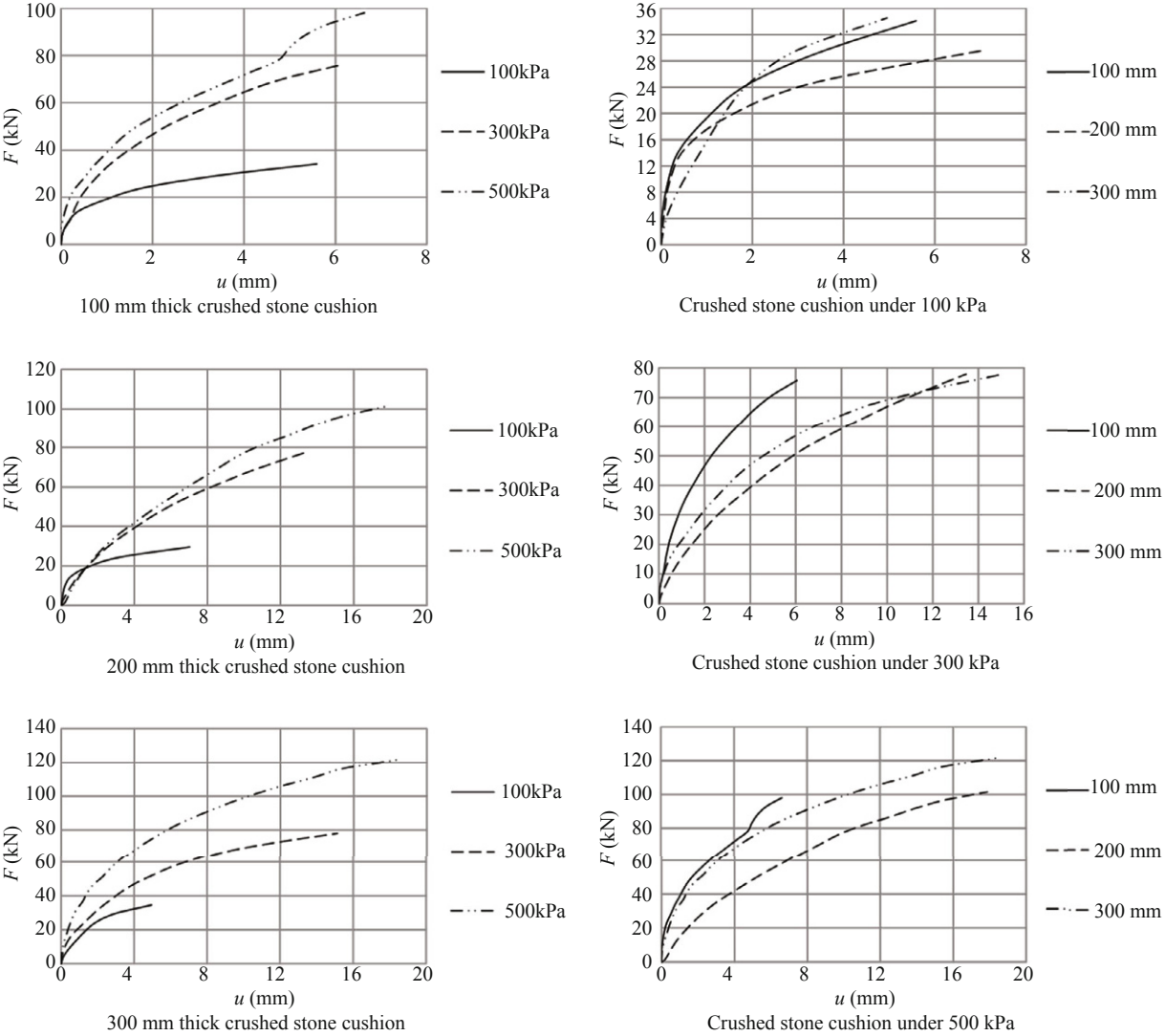


Fig. 5 F - u curves of 100 mm, 200 mm, and 300 mm thick crushed stone cushion under monotonic loading

Table 2 Normalized factor μ_n of different interfaces under different vertical pressure

Cushion Material		Crushed Stone			Sand			Mixture		
Thickness h_c (mm)		100	200	300	100	200	300	100	200	300
P_v (kPa)										
100		0.71	0.62	0.72	0.62	0.51	0.51	0.62	0.62	0.62
300		0.53	0.54	0.54	0.44	0.44	0.44	0.40	0.40	0.47
500		0.41	0.42	0.51	0.40	0.38	0.38	0.36	0.40	0.40

Table 3 Shear displacement u_{max} of different interfaces under different vertical pressure Unit: mm

Cushion Material		Crushed Stone			Sand			Mixture		
Thickness h_c (mm)		100	200	300	100	200	300	100	200	300
P_v (kPa)										
100		5.59	7.03	4.95	1.71	4.15	1.52	1.42	2.34	5.34
300		6.05	13.46	15.11	5.37	8.93	9.71	9.57	6.01	9.65
500		6.63	17.88	18.41	6.06	12.55	12.97	10.21	9.73	12.58

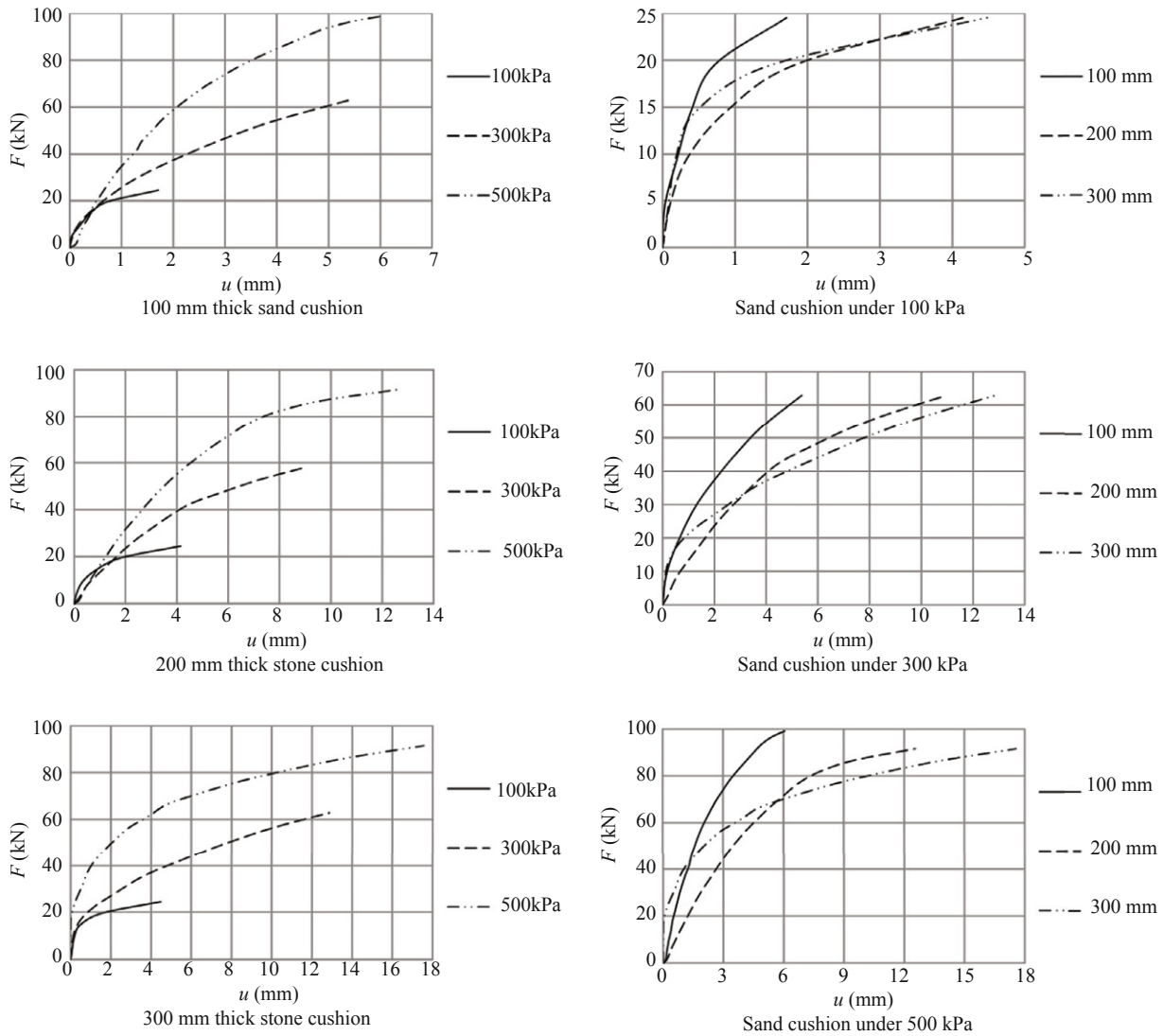


Fig. 6 F - u curves of 100 mm, 200 mm, and 300 mm thick medium-coarse sand cushion under monotonic loading

(4) With the same P_v and h_c , the $u_{\max}$ of crushed stone cushion is larger than that of the sand cushion, but the value of $u_{\max}$ of the mixture cushion seem to be irregular.

3.2 Physical interpretation

It should be expected that the interface shear resistance is positively correlated to the vertical pressure. The phenomenon of μ_n decreases as P_v increases was also observed in the monotonic loading test on rough sand/steel interface (Tejchman and Wu, 1995; Fakharian, 1996). This is most probably caused by the discontinuity of the cushion. Under high vertical pressure, particles in the shear zone adjacent to the interface are more easily to roll due to the failure of the particle interlock mechanism, which slows down the increase of the interface strength and leads to the decrease of μ_n when P_v increases. The shear displacement $u_{\max}$ is mainly comprised of the shear deformation of the cushion and slightly of the elastic compression of the particles. According to previous

studies (Tejchman and Wu, 1995; Frost *et al.*, 2004), the thickness of shear zone remains almost unchanged under different circumstances. Nevertheless, the shear strain γ increases with the increase of P_v . Hence, the $u_{\max}$ increases as P_v increases.

Roughness is a key factors to influence the interface shear properties. In this test, the concrete plate was precast, the roughness of the interface mainly depends on particle size of the cushion. The roughness coefficient can be computed as $R = D_{60} \cdot D_{10} / D_{50}$, in which the subscript refers to particle size of 60%, 50% and 10% finer size (Desai *et al.*, 1985). By referring to Fig. 4, R values of the three cushion materials are 1.8, 0.18 and 0.48 for crushed stone, sand and mixture respectively. Hence with the same P_v and h_c , the $P_{h\max}$ is the largest for the roughest crushed stone/concrete interface, medium for mixture cushion/concrete interface and smallest for sand/concrete interface. The value of $u_{\max}$ depends mainly on the initial porosity of different cushion materials. The initial porosity of the crushed stone is the largest, hence

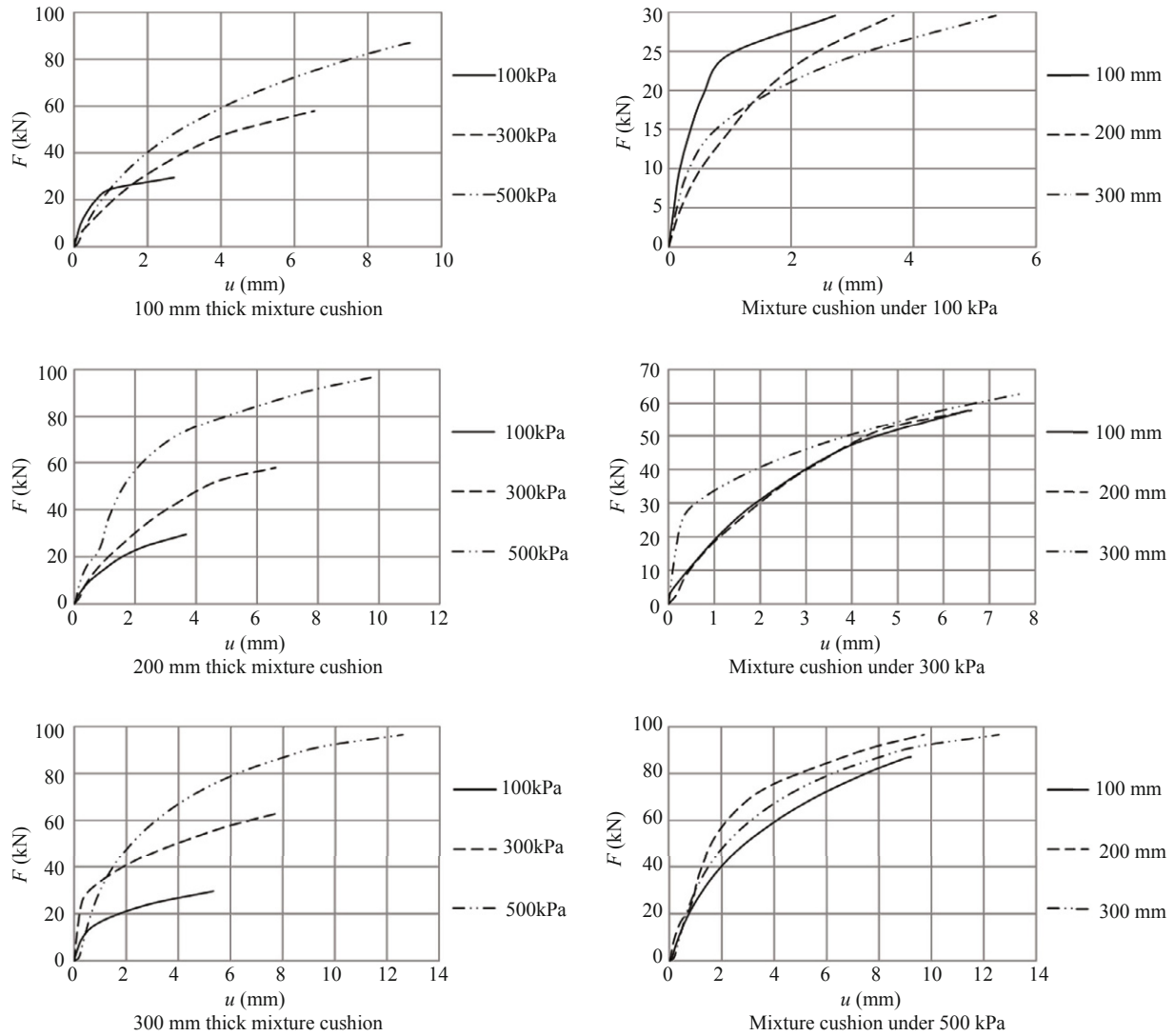


Fig. 7 F - u curves of 100 mm, 200 mm, and 300 mm thick sand-stone mixed cushion under monotonic loading

$u_{\max}$ is largest for it. The initial porosity for sand and mixture cushions are the same, for limestone is stiffer than most particles in river sand, the elastic compression between particles lead to the $u_{\max}$ of sand cushion is a little greater than that of the mixture cushion.

3.3 Quantitative analysis

The most significant factor for both μ_n and $u_{\max}$ is the vertical pressure P_v . The cushion material has some but not much effect on the variance of μ_n , while the influence of cushion thickness h_c can almost be neglected. For $u_{\max}$, the h_c has some impact on its variation while cushion material has little. Hence by not considering the insignificant factors, average values of μ_n and $u_{\max}$, together with the friction angle of the interface whose tangent value equals to μ_n can be calculated as Table 4. The friction angle δ_s of the sand cushion/raft interface varies from 21° to 29° , which is a little smaller than the test results by Desai *et al.* (Desai *et al.*, 1985). The

sand used in this study is less uniform than that used in Desai's test, hence the roughness of the interface is smaller, which is the reason for a smaller friction angle of the interface.

4 Cyclic loading test

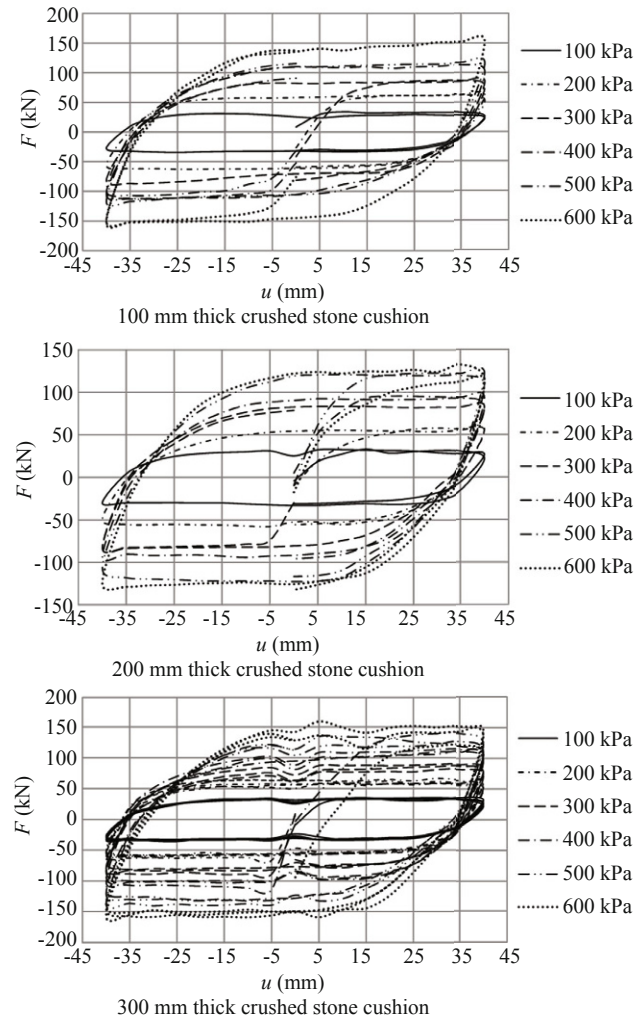
4.1 Test results and analysis

The F - u curves, or the hysteretic loops of the interfaces are shown in Fig. 8 through Fig. 10. Observations are listed as follows, and the notations are the same as the monotonic loading test.

(1) The hysteretic loops can be decomposed into 3 stages, which are: 1) the initial stage with large stiffness, or the elastic stage; 2) the second stage with smaller stiffness, or the plastic stage; and 3) the final stage with low stiffness almost equals to 0, or the sliding stage. Before the interlock between particles

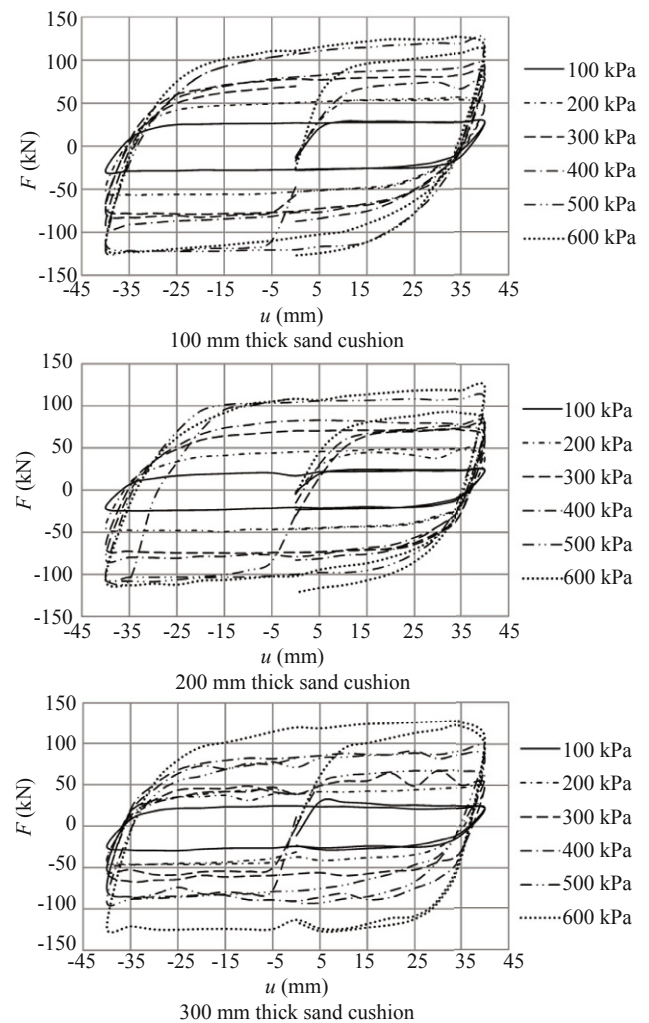
Table 4 Average values of indices with different factors

P_v (kPa)	μ_n			δ_s (°)			h_c (mm)	u_{max} (mm)		
	Cushion	Stone	Sand	Mixture	Stone	Sand	Mixture	100	200	300
100		0.68	0.55	0.62	34.3	28.7	31.8	2.91	4.51	3.94
300		0.54	0.44	0.42	28.2	23.7	22.9	7.00	9.47	11.49
500		0.45	0.39	0.39	24.1	21.1	21.1	7.63	13.39	14.65

**Fig. 8** Hysteretic loops of 100 mm, 200 mm, and 300 mm thick crushed stone cushion under cyclic loading

broke, the displacement was mainly caused by the compression between particles, and it was resilient and almost unchanged after multiple unloading-reloading cycles. After the interlock was broken, the displacement increased mainly because of the decrease of void ratio, which was due to the compaction of the cushion. Finally, the interface shear resistance was reached and the plate started to slide. The cyclic loading rate was greater than that of the monotonic loading, hence their force-displacement behaviors are different before reaching the interface shear resistance F_{max} .

(2) The elastic displacement u_1 at the end point

**Fig. 9** Hysteretic loops of 100 mm, 200 mm, and 300 mm thick medium-coarse sand cushion under cyclic loading

of the elastic stage is almost the same for different vertical pressures, cushion materials and thickness. Meanwhile, the plastic displacement u_2 , which is the total displacement at the end point of plastic stage increased with the increase of P_v . This phenomenon is consistent with that under monotonic loading.

(3) For cushions with the same material and thickness, the interface shear resistance F_{max} increases as P_v increases. Nevertheless, the normalized factor μ_n of the interface decreases as P_v increases. The reason for this phenomenon is the same as in monotonic loading test.

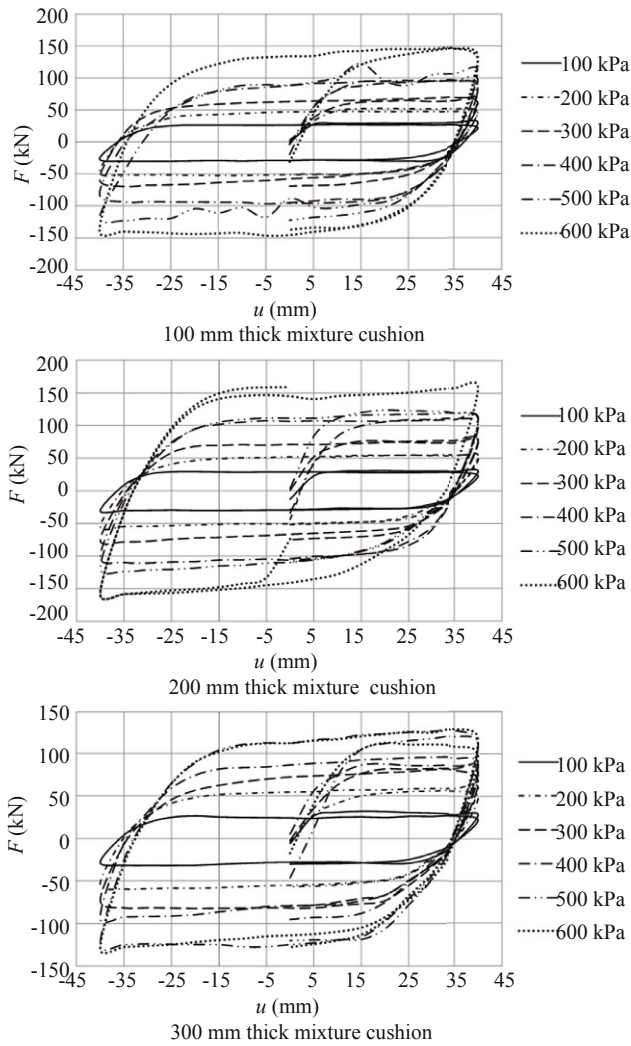


Fig. 10 Hysteretic loops of 100 mm, 200 mm, and 300 mm thick sand-stone mixed under cyclic loading

(4) With u_1 almost the same for the same interface under different P_v , the stiffness of the elastic stage K_1 increases as P_v increases. Meanwhile, the stiffness of the plastic stage K_2 has the same tendency as K_1 . The larger vertical pressure is, the denser cushion becomes, which further lead to higher stiffness under shear load.

(5) The loading rate has little effect on the shear behavior of the interface.

(6) The standard hysteretic loop and back-bone curve of the cushion/raft interface was proposed as shown in Fig. 11. The key indices of the “three-segment” back-bone curve include: the normalized factor of interface shear resistance μ_n , the elastic displacement u_1 , the plastic displacement or the shear displacement u_2 , the stiffness of the elastic segment K_1 and the stiffness of the plastic segment K_2 . The values of these key indices should be obtained by statistical analysis.

4.2 Quantitative analysis

According to the test plan, 4 main factors should

be taken account in the analysis, which are: 1) factor *A*: vertical pressure P_v (100~600 kPa, with 100 kPa as increment); 2) factor *B*: thickness of the cushion h_c (300 mm, 200 mm, 100 mm); 3) factor *C*: material type of the cushion (crushed stone, sand, mixture); and 4) factor *D*: loading rate (0.1 mm/s, 0.2 mm/s, 0.3 mm/s). The total number of combinations of these levels is $6 \times 3 \times 3 \times 3 = 54$, which is apparently time and cost consuming to be finished. If the proper statistical method is adopted, the quantitative analysis can be much more efficient and even more reliable.

Hence, statistical experiment using Taguchi's orthogonal array was carried out. Then the analysis of variance and the *F*-value significant test were conducted to quantitatively evaluate the effect of factors on the interface shear behavior, and to estimate the values of key indices of the “three-segment” back-bone curve. The best advantage of Taguchi's method is to conduct reliable statistical analysis with limited data sample. Detailed notations and procedures of the method, as well as the mathematical background can be referred to Taguchi *et al.* (2005).

5 Orthogonal array layout and results

The mixed orthogonal array of L_{18} ($6^1 \times 3^6$) is used, with 4 columns for factorial levels and 3 columns as blank contrast to quantify errors. By summarizing the test results, the elastic displacement is $u_1 = 2.5$ mm. Furthermore, the plastic displacement u_2 can be calculated with μ_n , K_1 and K_2 . Hence the indices induced by the main factors are: 1) the shear resistance P_{hmax} or the normalized factor μ_n ; 2) the stiffness of the elastic segment K_1 ; and 3) the stiffness of the plastic segment K_2 . The layout and results of the orthogonal array are shown in Table 5.

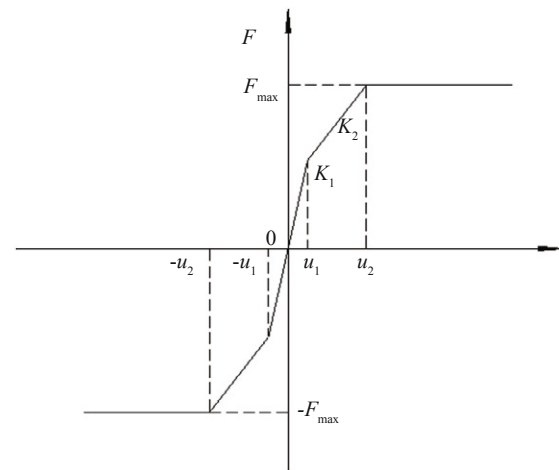


Fig. 11 “Three-segment” back-bone curve of the cushion under horizontal shear force

Table 5 Orthogonal array layout and results of cyclic loading test

Experiment No.	Column No.	Factors							μ_n	K_1 (kPa/mm)	K_2 (kPa/mm)
		<i>A</i>	<i>B</i>	<i>C</i>	Blank	<i>D</i>	Blank	Blank			
		1	2	3	4	5	6	7			
1	1	1	1	1	1	1	1	1	0.75	16.04	3.30
2	1	1	2	2	2	2	2	2	0.51	12.47	2.31
3	1	1	3	3	3	3	3	3	0.62	16.11	3.53
4	2	2	1	1	2	2	3	3	0.69	31.87	5.47
5	2	2	2	2	3	3	1	1	0.51	22.26	3.94
6	2	2	3	3	1	1	2	2	0.55	23.12	5.00
7	3	3	1	2	1	3	2	3	0.47	31.06	3.28
8	3	3	2	3	2	1	3	1	0.54	31.13	8.98
9	3	3	3	1	3	2	1	2	0.60	32.32	7.78
10	4	4	1	3	3	2	2	1	0.50	34.73	9.98
11	4	4	2	1	1	3	3	2	0.50	34.03	8.10
12	4	4	3	2	2	1	1	3	0.48	35.10	8.69
13	5	5	1	2	3	1	3	2	0.39	30.14	6.23
14	5	5	2	3	1	2	1	3	0.52	42.94	9.54
15	5	5	3	1	2	3	2	1	0.49	41.43	7.85
16	6	6	1	3	2	3	1	2	0.45	41.67	12.14
17	6	6	2	1	3	1	2	3	0.46	41.18	11.17
18	6	6	3	2	1	2	3	1	0.44	43.84	9.09

Note: The 1–6 levels of factor *A* are 100 kPa–600 kPa (100 kPa larger per grade); the 1–3 levels of factor *B* are 300 mm, 200 mm, 100 mm; the 1–3 levels of factor *C* are crushed stone, sand, mixed material (crushed stone + sand); the 1–3 levels of factor *D* are 0.1 mm/s, 0.2 mm/s, 0.3 mm/s.

6 Analysis of variance

With the test results, the total variation for each index, together with its decomposition, the variance of each factor can be calculated. Furthermore, the *F* values and contribution ratio of each factor can be obtained as shown in Table 6.

The significance of different factors is measured by *F* significant test, as well as the contribution ratio values. The *F* significant test is conducted by computing the *F* value of each factor and then comparing it with the reference *F* value of a specific significant level. If the variance of a factor is smaller than that of the error, then it should be re-classified as a source of error (with a triangular mark at the up-right corner of the factor name in the table). Hence the variance of the modified error can be obtained, the *F* value of each factor is then calculated as the variance ratio between itself and the modified error. The $F_{1-0.05}(f_1, f_e)$ stands for the reference *F* value with the 5% level of significance, while f_1, f_e are the degree of freedom of the factor and error respectively. If the factorial *F* value is smaller than the reference *F* value, the factor is judged as insignificant factor. Otherwise,

the significance of different factors rank in accordance with the corresponding *F* values. Meanwhile, the larger the contribution ratio of a factor is, the more impact this factor has on the index. The significance shown in Table 6 is the result based on both of the two values.

The same as intuitive analysis and in consistent with monotonic loading test result, the normalized factor of interface shear resistance μ_n is influenced mainly by the vertical pressure P_v and the cushion material type. The contribution ratio of these two factors are bigger than that of the error to a great extent, which means they should both be considered when calculating the parameters of the back-bone curve. For K_1 , the contribution ratio of factors *B*, *C* and *D* are smaller than that of the error. Hence the only significant factor is P_v . The most significant factor for K_2 is also P_v . Even though the cushion material has some effect on K_2 , it can be neglected in occasions requiring less precision, such as engineering practice.

The fact that loading rate (factor *D*) has little effect on the *F*-*u* relationship of the interface was also observed in other tests (Fakharian, 1996). Before sliding, the displacement of the plate is mainly caused by the shear deformation of the shear band formed near the interface.

Table 6 Analysis of variance of cyclic loading test

Index	Factor	Variance $\bar{S}$	$F = \bar{S} / S_e$	$F_{1-0.05}(f_1, f_e)$	Contribution ratio	Significance
Normalized factor of interface shear resistance μ_n	<i>A</i>	0.0249	9.35	3.69	0.55	**
	<i>B</i> ^Δ					
	<i>C</i>	0.0200	7.50	4.46	0.29	*
	<i>D</i> ^Δ	0.0021				
	<i>e</i>	0.0029				
	<i>e</i> ^Δ	0.0027			0.16	
Stiffness of the elastic segment K_1 (kPa/mm)	<i>A</i>	286.91	20.91	4.39	0.88	***
	<i>B</i>	17.90	1.30	5.14	0.02	
	<i>C</i>	20.96	1.53	5.14	0.03	
	<i>D</i>	19.21	1.40	5.14	0.02	
	<i>e</i>	13.72				
	<i>e</i> ^Δ	13.72			0.05	
Stiffness of the plastic segment K_2 (kPa/mm)	<i>A</i>	23.70	18.94	4.39	0.72	***
	<i>B</i>	7.75	6.19	5.14	0.09	
	<i>C</i>	10.48	8.38	5.14	0.13	*
	<i>D</i>	1.38	1.10	5.14	0.02	
	<i>e</i>	1.25				
	<i>e</i> ^Δ	1.25			0.05	

Note: The *B*^Δ means that factor *B* has little impact on μ_n and should be re-classified as a portion of the error.

The thickness of the shear band is supposed to be about $6D_{50}$ with D_{50} stands for 50% finer particle size (Frost *et al.*, 1999). Hence the cushion thickness (factor *B*) is insignificant for the interface shear behavior. Also, Frost *et al.* discovered that the angularity of particles had limited effect on the thickness of the shear band (Frost *et al.*, 2004), which explains the fact that cushion material has some but not big influence on the main indices of the interface.

It should be noted that the seismic absorption effect of the cushion on the superstructure is determined mainly by K_1 and the shear force acting on the cushion/raft interface. Only if the shear force is large enough to at least force the interface to step into the plastic stage of the cycle, will the ground motion energy be reduced by hysteretic dissipation. Otherwise, the only effect of the cushion is a minor reduction of the overall stiffness of the ground-raft-superstructure system, and the induced small reduction of seismic input, which are quite limited.

7 The values of indices

According to the analysis of variance, the most

significant factor for all 3 indices is the vertical pressure P_v . Hence the relationship between different indices and P_v is shown in Fig. 12. The regression equations between the key indices and P_v can also be obtained. As can be seen, the simple linear correlation is precise enough for computing the index values. For μ_n , the influence of cushion material cannot be ignored. Hence the curves of 3 cushion material are all presented in the figure. The regression equations for them are as follows:

$$\begin{cases} \mu_{n, \text{stone}} = -0.0004P_v + 0.7378; & R^2 = 0.9562 \\ \mu_{n, \text{sand}} = -0.0003P_v + 0.5977; & R^2 = 0.9462 \\ \mu_{n, \text{mixture}} = -0.0003P_v + 0.6387; & R^2 = 0.8330 \end{cases}$$

Such quantitative results may act as reference to engineers in designing practice, especially in evaluating the seismic performance of structures using NCPRF system.

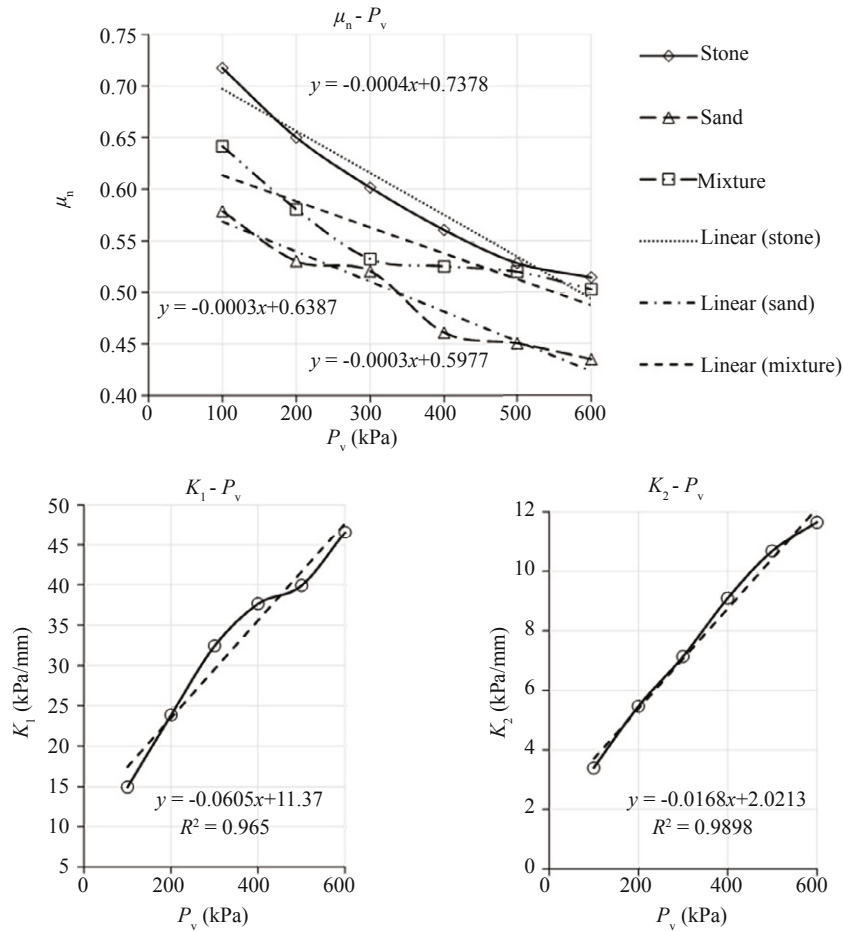


Fig. 12 Regression of main indices of the "three-segment" back-bone curve vs. vertical pressure

8 Conclusions

This paper studies the shear behavior of interfaces between concrete raft and different materials of cushion in the NCPRF under lateral loads. Both monotonic and cyclic loading tests were carried out on cushion/raft interfaces with different cushion material, cushion thickness h_c and under different vertical pressure P_v . Initiative analysis and physical interpretations are given based on observations. Furthermore, statistical method of orthogonal array are used to quantitatively analyze the test results. Conclusions can be drawn as follows:

(1) Under monotonic loading, the interface shear resistance P_{hmax} increases as the vertical pressure P_v increases. Nevertheless the normalized factor of interface shear resistance μ_n has the opposite tendency. The cushion material also has some but not much effect on P_{hmax} or μ_n . The values of these two parameters decrease in the sequence of crushed stone, stone-sand mixture and sand cushion.

(2) The concrete plate underwent a relatively large horizontal shear displacement u_{max} before sliding. The displacement was caused by the accumulation of shear deformation of the cushion. With the increase of P_v , u_{max}

increases.

(3) The friction angle of the interface δ_s varies from 20° to 35° , μ_n varies from 0.40 to 0.70, while u_{max} varies from 3 mm to 15 mm. These values can be reference to engineering practice.

(4) Under cyclic loading, the shear behavior of the cushion/raft interface can be abstracted as a "three-segment" back-bone curve as shown in Fig. 11. The main parameters include the interface shear resistance P_{hmax} or its normalized factor μ_n , the elastic displacement u_1 which is resilient during unloading, the plastic displacement u_2 with which the sliding of the plate happens, the elastic stiffness K_1 and the plastic stiffness K_2 .

(5) By initiative and detailed statistical analysis, the significance of different factors on the parameters mentioned above are obtained and summarized. The value of u_1 is almost a fixed number, while for all the rest parameters, the most significant factor is still P_v . For P_{hmax} and μ_n , the cushion material also have some contribution to their variation. As for u_2 , K_1 and K_2 , P_v is almost the only significant influence factor. Meanwhile, the cushion material has some but quite limited effect on u_2 and K_2 , such effect can be neglected in industrial practice.

(6) The value of u_1 is 2.5 mm in all circumstances. The test results of the rest 3 parameters have been correlated to P_v , and categorized as different cushion materials for μ_n . In practice, with the vertical load and geometric dimensions of the raft, all the parameters can be calculated and serve as initial input for further dynamic analysis of the ground-cushion-structure system. Nevertheless, it should be noted that the above conclusions are based on limited number of tests. More tests are needed to generalize the conclusions.

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