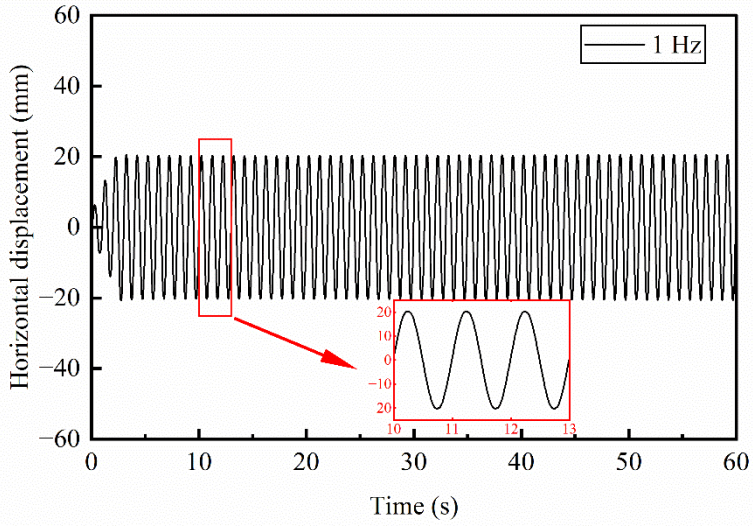
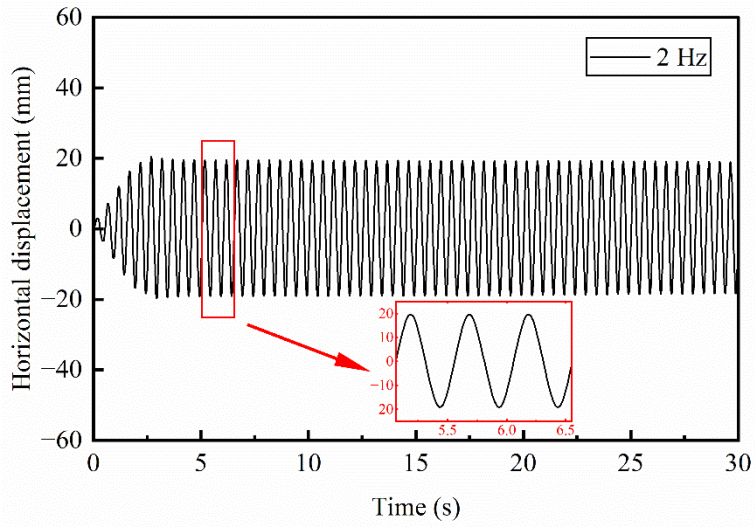
Supplementary Materials

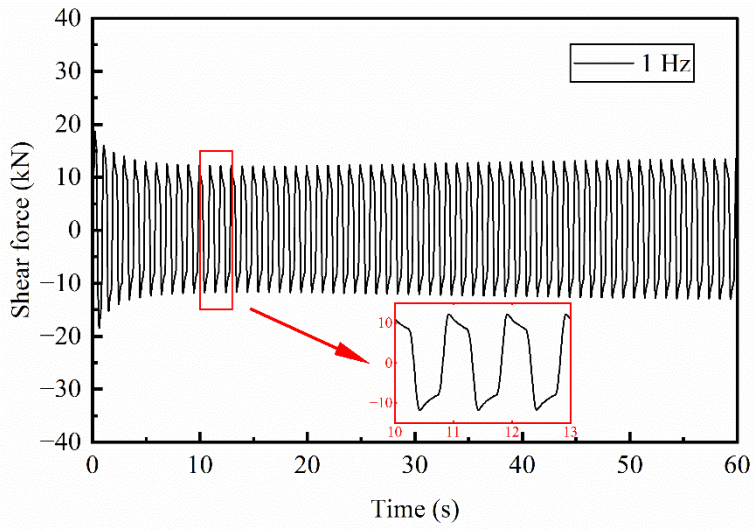


(a) 1 Hz

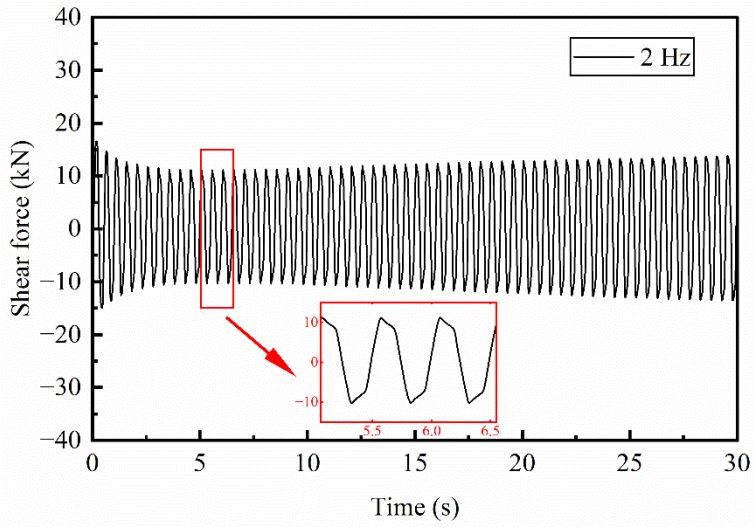


(b) 2 Hz

Figure S1. Horizontal displacement-Time history of representative condition(400 kPa, 20mm)



(a) 1 Hz



(b) 2 Hz

Figure S2. Shear force-Time history of representative condition(400 kPa, 20mm)

Table S1. Prescribed and measured loading characteristics for all cyclic shear test conditions

Prescribed frequency (Hz)	σn (kPa)	Prescribed amplitude (mm)	Measured amplitude (mm)	Measured amplitude SD (mm)	Mean measured amplitude (11–60 cycles) (mm)	Mean measured amplitude SD (mm)	Error vs prescribed (%)	Measured period (s)	Period SD (s)
0.5	100	5	5.038	0.014	5.036	0.0025	0.71	1.9975	0.0072
		10	10.041	0.013	10.040	0.001	0.4	1.9963	0.0077

		20	19.913	0.018	19.910	0.0015	-0.45	1.9968	0.0050
	200	5	5.025	0.017	5.021	0.0023	0.42	1.9958	0.0056
		10	9.971	0.017	9.969	0.0019	-0.31	1.9960	0.0055
		20	19.821	0.020	19.818	0.0033	-0.91	1.9972	0.0055
	400	5	4.996	0.028	4.990	0.0013	-0.2	1.9963	0.0058
		10	10.013	0.040	10.006	0.0022	0.06	1.9972	0.0058
		20	19.734	0.057	19.728	0.0075	-1.36	1.9970	0.0059
1.0	100	5	4.925	0.474	5.008	0.0025	0.16	0.9988	0.0058
		10	9.586	0.908	9.744	0.0063	-2.56	0.9977	0.0042
		20	19.096	1.846	19.419	0.0108	-2.9	0.9983	0.0037
	200	5	4.817	0.471	4.898	0.0039	-2.04	0.9968	0.0050
		10	9.648	0.919	9.805	0.0085	-1.95	0.9990	0.0060
		20	19.261	1.866	19.588	0.0123	-2.06	0.9992	0.0042
	400	5	4.920	0.516	5.004	0.0126	0.08	0.9978	0.0100
		10	9.798	0.958	9.946	0.017	-0.54	0.9980	0.0065
		20	20.029	1.942	20.379	0.1144	1.9	0.9983	0.0052
2.0	100	5	4.921	0.905	5.173	0.0163	3.47	0.4983	0.0052
		10	9.552	1.671	10.012	0.0281	0.12	0.4992	0.0059
		20	19.039	2.829	19.688	0.0284	-1.56	0.5003	0.0086
	200	5	4.663	0.879	4.907	0.0144	-1.85	0.5002	0.0122
		10	9.459	1.702	9.932	0.0305	-0.68	0.4987	0.0059
		20	18.897	2.850	19.579	0.0277	-2.1	0.5000	0.0086
	400	5	4.604	0.942	4.909	0.0716	-1.82	0.4987	0.0039
		10	8.900	1.728	9.420	0.0396	-5.8	0.4997	0.0086
		20	18.495	2.621	19.061	0.0189	-4.69	0.4997	0.0080

Note: Measured amplitude and measured period are the mean values over the 60 loading cycles. Amplitude SD and Period SD are reported as the standard deviation of the measured amplitude and period over the 60 cycles.

Table S2. Positive- and negative-direction cyclic shear resistance and peak-cycle information for all 27 test conditions.

			Positive loading direction			Negative loading direction		
f (Hz)	σ_n (kPa)	A (mm)	Peak resistance $\tau_{p,+}$ (kPa)	Peak cycle $N_{p,+}$	60th-cycle resistance $\tau_{60,+}$ (kPa)	Peak resistance $\lvert\tau_{p,-}\rvert$ (kPa)	Peak cycle $N_{p,-}$	60th-cycle resistance $\lvert\tau_{60,-}\rvert$ (kPa)
0.5	100	5	61.5	1	50.9	54.7	1	47.5
		10	63.2	1	48.4	52.8	1	44.2
		20	68.7	1	51.0	61.6	1	46.1
	200	5	107.2	1	83.3	95.4	1	75.2
		10	109.9	1	83.8	87.4	1	67.1
		20	88.9	1	67.4	84.5	1	66.2
	400	5	198.5	1	130.7	187.6	1	125.0
		10	203.6	1	130.4	200.0	1	134.5
		20	181.6	1	128.3	199.8	1	148.7
1.0	100	5	58.8	2	49.5	50.8	1	43.6
		10	62.7	1	50.5	54.5	1	45.0
		20	61.9	1	44.0	72.5	1	54.4
	200	5	107.5	2	81.5	98.5	2	74.6
		10	86.5	1	59.5	109.5	1	87.0
		20	95.0	1	66.5	99.2	1	76.7
	400	5	195.6	3	133.5	194.4	2	127.0
		10	204.0	2	134.8	179.7	1	113.1
		20	207.9	1	149.8	205.1	1	143.9
2.0	100	5	56.8	3	46.7	51.1	3	41.6
		10	57.0	1	46.0	49.4	2	41.7
		20	60.4	1	44.4	76.7	1	56.4
	200	5	82.1	3	77.2	72.2	6	68.6
		10	90.1	2	65.2	99.5	2	72.4
		20	94.6	1	70.0	102.8	1	80.7
	400	5	191.3	5	126.4	179.8	5	118.7
		10	196.3	4	116.9	225.3	3	142.8
		20	184.2	1	153.2	166.5	1	151.0

Note: Positive- and negative-direction resistance values were extracted separately. The resistance ratio used in the main text was calculated from the positive loading direction. The peak-cycle number identifies the cycle at which the corresponding directional maximum resistance occurred.

Table S3a. Directional secant stiffness, hysteresis-loop area, reference recoverable energy, and equivalent damping ratio for the first complete cycle after the measured displacement amplitude stabilized at the prescribed value.

f (Hz)	σ_n (kPa)	A (mm)	K_1 (kPa/mm)	K_2 (kPa/mm)	ΔW (kPa·mm)	$W_{s,1}$ (kPa·mm)	$W_{s,2}$ (kPa·mm)	β (–)
0.5	100	5	12.30	10.93	793.9	153.7	136.6	0.437
		10	6.32	5.28	1730.1	315.9	263.8	0.479
		20	3.44	3.08	3953.5	687.0	616.2	0.484
	200	5	21.43	19.07	1261.5	267.9	238.4	0.398
		10	10.99	8.74	2923.1	549.4	436.8	0.478
		20	4.44	4.22	5346.5	888.9	845.0	0.491
	400	5	39.70	37.51	2274.1	496.2	468.9	0.375
		10	20.36	20.00	5799.2	1018.2	1000.1	0.457
		20	9.08	9.99	11241.0	1816.4	1998.2	0.470
1.0	100	5	11.17	9.56	599.9	139.6	119.5	0.371
		10	5.75	5.10	1525.3	287.7	254.9	0.449
		20	2.49	3.08	3264.9	497.1	615.7	0.472
	200	5	19.64	17.62	1013.3	245.5	220.3	0.347
		10	7.35	9.87	2491.5	367.3	493.4	0.471
		20	3.58	4.22	4691.2	716.4	843.4	0.482
	400	5	35.65	32.96	1910.1	445.6	412.1	0.355
		10	16.71	14.13	4443.1	835.4	706.7	0.462
		20	7.40	7.31	9082.2	1480.0	1461.0	0.492
2.0	100	5	10.51	9.43	341.3	131.4	117.9	0.219
		10	5.09	4.65	1121.8	254.5	232.3	0.367
		20	2.50	3.08	2791.2	499.0	615.8	0.403
	200	5	19.47	17.20	519.3	243.4	214.9	0.181
		10	7.69	8.38	1720.7	384.6	419.2	0.341
		20	3.60	4.15	3789.9	720.3	830.4	0.391
	400	5	32.38	30.67	685.8	404.8	383.3	0.139
		10	14.16	16.66	2707.4	708.2	833.1	0.281
		20	6.52	6.07	6246.7	1304.6	1213.0	0.395

Table S3b. Directional secant stiffness, hysteresis-loop area, reference recoverable energy, and equivalent damping ratio for the 60th cycle.

f (Hz)	σ_n (kPa)	A (mm)	K_1 (kPa/mm)	K_2 (kPa/mm)	ΔW (kPa·mm)	$W_{s,1}$ (kPa·mm)	$W_{s,2}$ (kPa·mm)	β (–)
0.5	100	5	10.18	9.49	728.5	127.3	118.6	0.472
		10	4.84	4.42	1476.9	242.0	221.1	0.509
		20	2.55	2.30	3081.0	510.4	460.9	0.506
	200	5	16.65	15.04	1158.6	208.2	188.1	0.467
		10	8.38	6.71	2418.0	418.8	335.3	0.517
		20	3.37	3.31	4356.3	673.7	661.9	0.519
	400	5	26.14	25.00	1874.2	326.8	312.5	0.467
		10	13.04	13.45	4190.5	651.9	672.7	0.504
		20	6.42	7.43	8651.2	1283.0	1486.7	0.500
1.0	100	5	9.91	8.72	592.8	123.9	108.9	0.407

		10	5.05	4.50	1368.8	252.5	225.2	0.458
		20	2.20	2.72	2880.0	440.1	543.7	0.471
		5	16.30	14.91	955.3	203.8	186.4	0.390
	200	10	5.95	8.70	2126.3	297.6	435.1	0.479
		20	3.33	3.84	4361.4	665.0	767.0	0.487
		5	26.70	25.41	1662.8	333.8	317.6	0.407
	400	10	13.48	11.31	3656.6	673.9	565.4	0.473
		20	7.49	7.19	9374.7	1497.8	1438.9	0.508
		5	9.33	8.32	379.6	116.7	104.0	0.275
	100	10	4.60	4.17	1035.3	230.1	208.3	0.377
		20	2.22	2.82	2521.6	444.3	564.4	0.404
		5	15.44	13.71	567.0	193.0	171.4	0.249
2.0	200	10	6.52	7.24	1578.0	325.9	362.0	0.366
		20	3.50	4.03	3724.6	700.4	806.6	0.395
		5	25.29	23.73	952.7	316.1	296.6	0.248
	400	10	11.69	14.28	2681.6	584.4	713.9	0.332
		20	7.66	7.55	6579.8	1532.1	1509.8	0.344