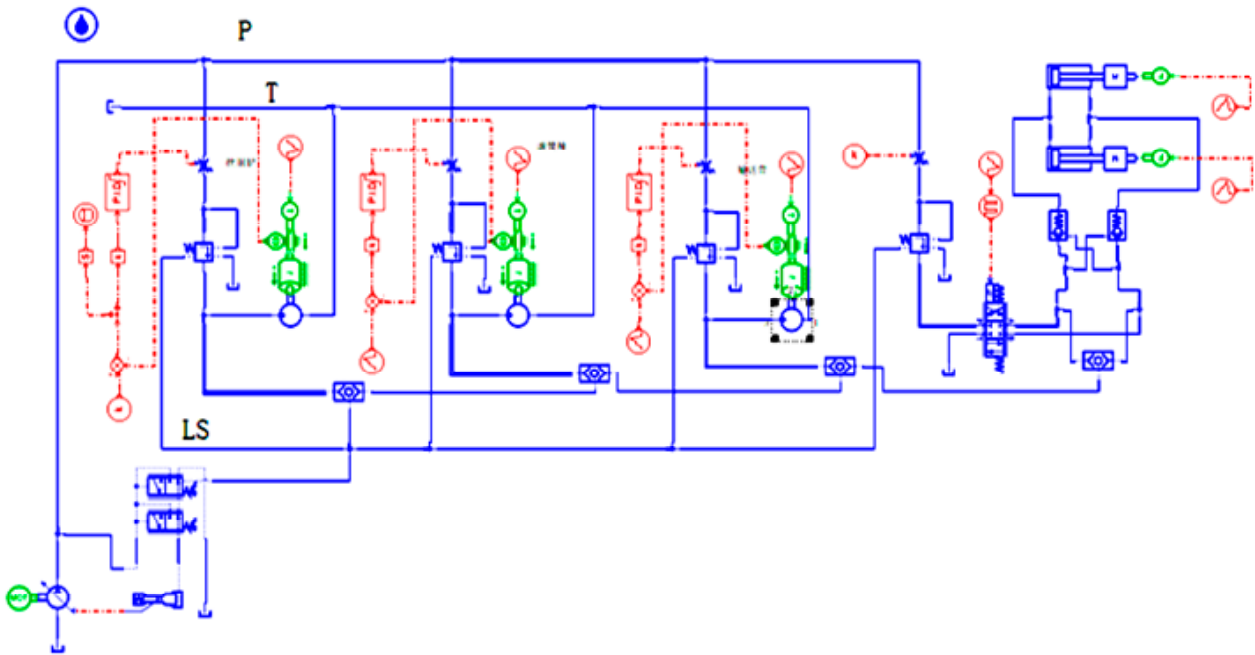


Supplementary Figures and Tables

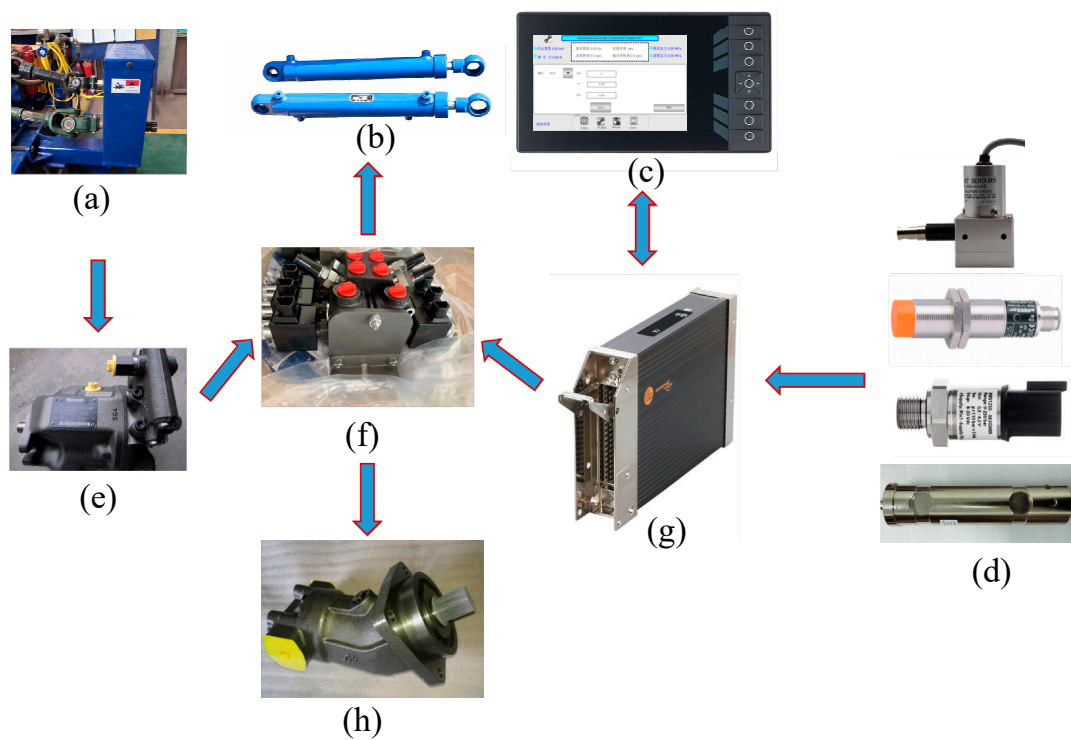
Supplementary Table S1. Mechanical and physical properties of Jerusalem artichoke crop.

Parameter	Roots	Tuber	Stem
Poisson's ratio	0.380	0.408	0.350
Shear modulus (Pa)	4.783×10^6	4.226×10^6	2.72×10^8
Density/($\text{kg} \cdot \text{m}^{-3}$).	1132	1184.4	250.75
X-steel static friction	0.511	0.446	0.5
X-steel rolling friction	0.201	0.275	0.05
X-steel restitution	0.320	0.620	0.53

X: Either root or tuber or stem.



Supplementary Figure S1. Hydraulic system circuit diagram.



Supplementary Figure S2. Control and measuring equipment: (a) PTO input, (b) hydraulic cylinder, (c) user interface module, (d) information acquisition module, (e) hydraulic pump, (f) hydraulic valve module, (g) PLC unit, and (h) hydraulic motor.



Supplementary Figure S3. Field soil moisture meter (left) and soil cone penetrometer (right).

Supplementary Table S2. Static angle of repose factors and level.

Factor	Name	Type	Minimum	Maximum	Mean	Std. Dev.
A	Coefficient of restitution: soil- root	Numeric	0.30	0.60	0.44	0.12
B	Coefficient of restitution: soil-tuber	Numeric	0.30	0.60	0.45	0.13
C	Coefficient of restitution: soil-stem	Numeric	0.30	0.60	0.45	0.13
D	Coefficient of static friction: root-soil	Numeric	0.10	0.30	0.20	0.08
E	Coefficient of static friction: tuber-soil	Numeric	0.20	0.40	0.30	0.08
F	Coefficient of static friction: stem-soil	Numeric	0.15	0.30	0.23	0.06
G	Coefficient of rolling friction: root-soil	Numeric	0.01	0.03	0.02	0.01
H	Coefficient of rolling friction: tuber-soil	Numeric	0.02	0.20	0.11	0.08
I	Coefficient of rolling friction: stem-soil	Numeric	0.05	0.15	0.10	0.04

Supplementary Table S3. I-optimal experimental design and data for static angle of repose simulation.

Run	A	B	C	D	E	F	G	H	I	AoR (°)
1	0.48	0.30	0.48	0.10	0.20	0.30	0.02	0.13	0.10	38.71
2	0.60	0.60	0.60	0.10	0.20	0.30	0.03	0.02	0.15	33.33
3	0.51	0.49	0.30	0.26	0.30	0.15	0.02	0.13	0.05	34.26
4	0.30	0.30	0.30	0.10	0.40	0.30	0.03	0.20	0.15	21.60
5	0.30	0.60	0.60	0.30	0.29	0.15	0.03	0.02	0.15	28.99
6	0.43	0.42	0.54	0.30	0.36	0.30	0.01	0.11	0.07	33.45
7	0.50	0.30	0.30	0.30	0.32	0.30	0.02	0.17	0.15	36.14
8	0.38	0.60	0.33	0.20	0.32	0.30	0.01	0.02	0.12	35.75
9	0.30	0.60	0.60	0.18	0.40	0.15	0.01	0.20	0.05	39.85
10	0.60	0.60	0.44	0.11	0.30	0.25	0.01	0.11	0.05	30.56
11	0.30	0.30	0.45	0.17	0.28	0.15	0.02	0.13	0.05	26.45
12	0.60	0.30	0.30	0.30	0.22	0.26	0.01	0.04	0.09	20.97
13	0.60	0.30	0.30	0.10	0.20	0.15	0.03	0.20	0.05	33.36
14	0.48	0.36	0.60	0.10	0.39	0.23	0.02	0.20	0.05	28.25
15	0.60	0.47	0.45	0.23	0.20	0.15	0.02	0.02	0.14	25.73
16	0.30	0.30	0.60	0.30	0.20	0.30	0.03	0.20	0.05	33.28
17	0.30	0.60	0.60	0.10	0.20	0.30	0.01	0.20	0.09	40.75
18	0.34	0.41	0.56	0.15	0.20	0.20	0.03	0.20	0.15	22.77
19	0.30	0.60	0.47	0.30	0.20	0.20	0.01	0.02	0.05	19.57
20	0.43	0.30	0.30	0.30	0.20	0.15	0.02	0.20	0.14	22.01
21	0.32	0.30	0.60	0.30	0.40	0.26	0.02	0.20	0.15	37.77
22	0.30	0.30	0.60	0.30	0.20	0.30	0.01	0.02	0.15	39.41
23	0.60	0.30	0.60	0.14	0.40	0.15	0.03	0.10	0.15	26.98
24	0.60	0.60	0.30	0.30	0.40	0.30	0.01	0.20	0.15	25.47
25	0.30	0.34	0.30	0.30	0.40	0.15	0.01	0.02	0.15	21.34
26	0.30	0.30	0.30	0.10	0.40	0.30	0.01	0.02	0.05	27.80
27	0.30	0.41	0.38	0.23	0.27	0.23	0.01	0.20	0.11	39.61

28	0.43	0.42	0.60	0.10	0.27	0.15	0.01	0.02	0.08	37.93
29	0.51	0.60	0.59	0.19	0.40	0.30	0.03	0.20	0.11	26.65
30	0.41	0.47	0.45	0.30	0.40	0.15	0.03	0.20	0.08	36.04
31	0.33	0.60	0.39	0.14	0.40	0.30	0.01	0.20	0.05	30.11
32	0.60	0.60	0.30	0.30	0.20	0.30	0.03	0.02	0.05	28.05
33	0.53	0.30	0.53	0.30	0.28	0.17	0.03	0.02	0.05	25.50
34	0.40	0.60	0.30	0.10	0.40	0.15	0.03	0.02	0.07	33.10
35	0.60	0.60	0.30	0.21	0.30	0.22	0.03	0.13	0.15	20.73
36	0.58	0.41	0.30	0.14	0.20	0.30	0.01	0.20	0.15	31.37
37	0.30	0.41	0.30	0.22	0.20	0.25	0.03	0.05	0.09	36.08
38	0.33	0.47	0.32	0.23	0.38	0.15	0.03	0.07	0.15	27.14
39	0.60	0.44	0.30	0.10	0.40	0.30	0.02	0.07	0.10	30.37
40	0.54	0.40	0.60	0.20	0.20	0.30	0.02	0.02	0.05	30.36
41	0.60	0.59	0.50	0.10	0.30	0.15	0.02	0.20	0.13	24.52
42	0.34	0.53	0.49	0.10	0.40	0.23	0.02	0.08	0.15	32.07
43	0.30	0.54	0.53	0.10	0.30	0.30	0.03	0.05	0.05	34.05
44	0.30	0.41	0.38	0.23	0.27	0.23	0.01	0.20	0.11	36.15
45	0.60	0.30	0.60	0.10	0.37	0.30	0.01	0.02	0.15	33.65
46	0.43	0.30	0.32	0.10	0.29	0.21	0.02	0.02	0.15	29.11
47	0.46	0.41	0.60	0.10	0.40	0.29	0.01	0.02	0.05	29.48
48	0.60	0.60	0.60	0.30	0.40	0.17	0.02	0.02	0.05	28.66
49	0.30	0.30	0.59	0.18	0.40	0.23	0.03	0.02	0.10	31.26
50	0.30	0.60	0.30	0.10	0.20	0.15	0.01	0.12	0.15	22.70
51	0.60	0.30	0.38	0.25	0.35	0.30	0.03	0.20	0.05	32.06
52	0.53	0.30	0.36	0.17	0.40	0.18	0.01	0.17	0.11	28.14
53	0.60	0.30	0.60	0.30	0.20	0.15	0.01	0.20	0.05	20.95
54	0.60	0.43	0.60	0.30	0.25	0.26	0.03	0.14	0.11	35.15
55	0.56	0.60	0.37	0.30	0.20	0.29	0.01	0.20	0.08	30.78
56	0.30	0.60	0.30	0.30	0.40	0.26	0.03	0.11	0.05	23.60
57	0.47	0.60	0.60	0.26	0.26	0.20	0.01	0.12	0.15	37.33
58	0.30	0.60	0.42	0.30	0.20	0.30	0.02	0.20	0.15	28.13
59	0.50	0.41	0.42	0.29	0.40	0.29	0.03	0.02	0.15	30.97
60	0.50	0.60	0.59	0.19	0.20	0.16	0.03	0.12	0.05	20.18
61	0.41	0.60	0.30	0.10	0.21	0.26	0.02	0.20	0.05	26.96

A: Coefficient of restitution: soil- root; B: Coefficient of restitution: soil-tuber; C: Coefficient of restitution: soil-stem; D: Coefficient of static friction: root-soil; E: Coefficient of static friction: tuber-soil; F: Coefficient of static friction: stem-soil; G: Coefficient of rolling friction: root-soil; H: Coefficient of rolling friction: tuber-soil; I: Coefficient of rolling friction: stem-soil; AoR: Static angle of repose.

Supplementary Table S4. ANOVA results for static angle of repose simulation (sandy loam soil).

Source	Sum of Squares	df	Mean Square	F-value	P-value	Remark
Model	1891.45	36	52.54	24.16	< 0.0001*	significant
A	34.06	1	34.06	15.66	0.0006*	
B	3.43	1	3.43	1.58	0.2212**	
C	50.3	1	50.3	23.13	< 0.0001*	
D	7.98	1	7.98	3.67	0.0675**	
E	5.92	1	5.92	2.72	0.1119**	
F	192.47	1	192.47	88.5	< 0.0001*	
G	44.44	1	44.44	20.43	0.0001*	
H	3.2	1	3.2	1.47	0.2367**	
I	0.0231	1	0.0231	0.0106	0.9187**	
AF	32.04	1	32.04	14.73	0.0008*	
AG	34.34	1	34.34	15.79	0.0006*	
AI	6.82	1	6.82	3.13	0.0893**	
BC	23.44	1	23.44	10.78	0.0031*	
BE	22.33	1	22.33	10.27	0.0038*	
BF	34.01	1	34.01	15.64	0.0006*	
BG	140.55	1	140.55	64.63	< 0.0001*	
BH	36.21	1	36.21	16.65	0.0004*	
CE	27.99	1	27.99	12.87	0.0015*	
CG	33.11	1	33.11	15.22	0.0007*	
CI	159.83	1	159.83	73.49	< 0.0001*	
DG	24.84	1	24.84	11.42	0.0025*	
DH	129.57	1	129.57	59.58	< 0.0001*	
DI	50.92	1	50.92	23.41	< 0.0001*	
EF	222.05	1	222.05	102.1	< 0.0001*	
EH	7.89	1	7.89	3.63	0.0688**	
FI	66.17	1	66.17	30.42	< 0.0001*	
GH	71.59	1	71.59	32.92	< 0.0001*	
GI	36.29	1	36.29	16.68	0.0004*	
HI	42.46	1	42.46	19.52	0.0002*	
A ²	6.53	1	6.53	3	0.0959**	
B ²	86.59	1	86.59	39.82	< 0.0001*	
C ²	11.72	1	11.72	5.39	0.0291*	
E ²	60.65	1	60.65	27.88	< 0.0001*	
F ²	18.99	1	18.99	8.73	0.0069*	
I ²	67.82	1	67.82	31.18	< 0.0001*	
Residual	52.2	24	2.17			not significant
Lack of Fit	46.21	23	2.01	0.3358	0.9022	
Pure Error	5.98	1	5.98			
Cor Total	1943.65	60				

*: Statistically significant (p<0.05).

** : Statistically not significant ($p>0.05$)

A: Coefficient of restitution: soil- root; B: Coefficient of restitution: soil-stem; C: Coefficient of static friction: root-soil; E: Coefficient of static friction: tuber-soil; F: Coefficient of static friction: stem-soil; G: Coefficient of rolling friction: root-soil; H: Coefficient of rolling friction: tuber-soil; I: Coefficient of rolling friction: stem-soil .

Supplementary Table S5. Box-Behnken experimental design and result for the angle of repose simulation (Clay soil).

Run	A	B	C	D (Jm^{-3})	Angle of repose ($^{\circ}$)
1	0.2	0.45	0.15	26000	36.87
2	0.4	0.45	0.5	38000	54.53
3	0.4	0.45	0.325	26000	47.97
4	0.4	0.2	0.15	26000	23.88
5	0.4	0.2	0.325	38000	27.54
6	0.6	0.45	0.5	26000	48.85
7	0.2	0.2	0.325	26000	30.34
8	0.4	0.45	0.325	26000	45.61
9	0.4	0.45	0.15	14000	36.95
10	0.6	0.2	0.325	26000	25.39
11	0.4	0.7	0.325	38000	48.90
12	0.6	0.45	0.325	38000	47.66
13	0.2	0.45	0.325	38000	49.22
14	0.4	0.45	0.325	26000	46.28
15	0.4	0.2	0.325	14000	29.22
16	0.6	0.45	0.15	26000	34.43
17	0.6	0.45	0.325	14000	38.24
18	0.6	0.7	0.325	26000	47.78
19	0.4	0.45	0.5	14000	51.07
20	0.2	0.45	0.5	26000	53.74
21	0.4	0.2	0.5	26000	29.43
22	0.4	0.45	0.325	26000	49.23
23	0.4	0.7	0.325	14000	48.91
24	0.4	0.45	0.15	38000	35.37
25	0.4	0.7	0.15	26000	36.96
26	0.2	0.7	0.325	26000	52.14
27	0.4	0.45	0.325	26000	46.92

28	0.2	0.45	0.325	14000	50.26
29	0.4	0.7	0.5	26000	55.60

A: Restitution; B: Static Friction; C: Rolling Friction; D: Cohesive Energy Density.

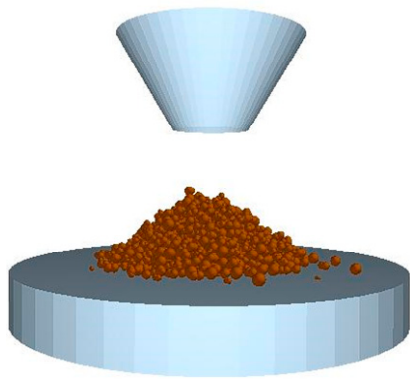
Supplementary Table S6. ANOVA results for static angle of repose simulation (clay soil).

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remarks
Model	2553.04	14	182.36	60.06	< 0.0001*	significant
A-Restitution	76.12	1	76.12	25.07	0.0002*	
B-Static Friction	1291.37	1	1291.37	425.29	< 0.0001*	
C-Rolling Friction	656.73	1	656.73	216.28	< 0.0001*	
D-Cohesive Energy Density	6.10	1	6.10	2.01	0.1781**	
AB	0.0884	1	0.0884	0.0291	0.8669**	
AC	1.51	1	1.51	0.4964	0.4926**	
AD	27.35	1	27.35	9.01	0.0095*	
BC	42.78	1	42.78	14.09	0.0021*	
BD	0.6965	1	0.6965	0.2294	0.6394**	
CD	6.37	1	6.37	2.10	0.1695**	
A ²	2.52	1	2.52	0.8291	0.3779**	
B ²	412.88	1	412.88	135.97	< 0.0001*	
C ²	50.10	1	50.10	16.50	0.0012*	
D ²	0.4220	1	0.4220	0.1390	0.7149**	
Residual	42.51	14	3.04			
Lack of Fit	34.33	10	3.43	1.68	0.3258	not significant
Pure Error	8.18	4	2.04			
Cor Total	2595.55	28				

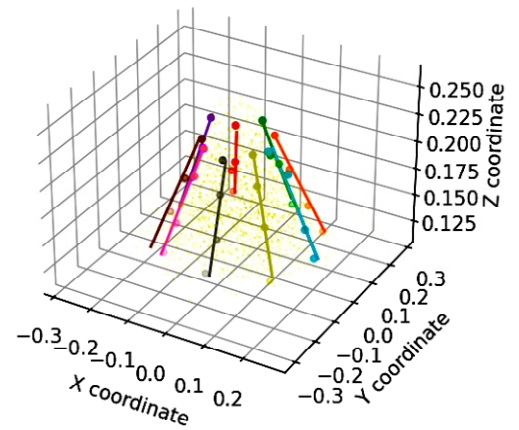
A: Restitution B: Static Friction C: Rolling Friction D: Cohesive Energy Density

*: Statistically significant (p<0.05)

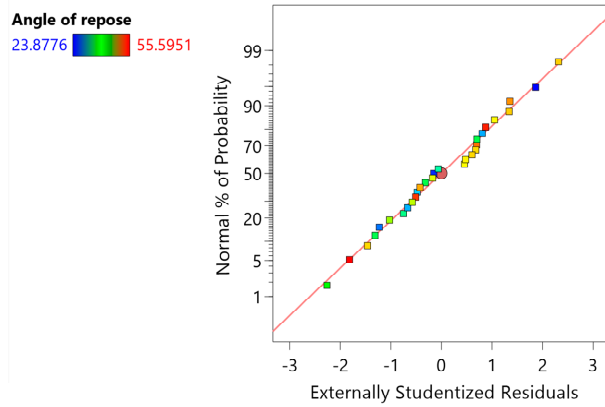
**: Statistically not significant (p>0.05).



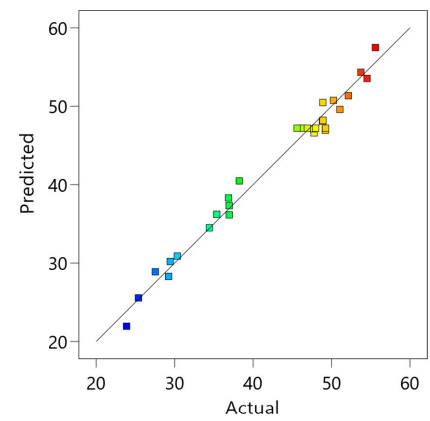
(a)



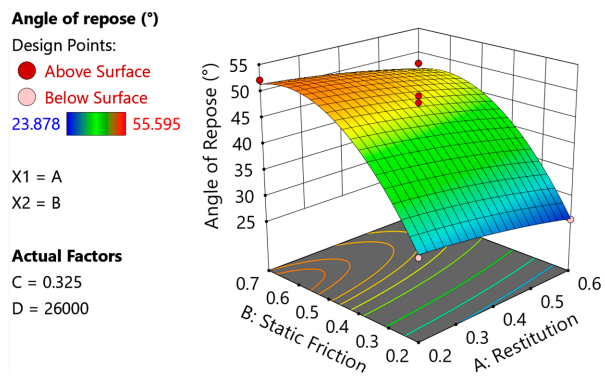
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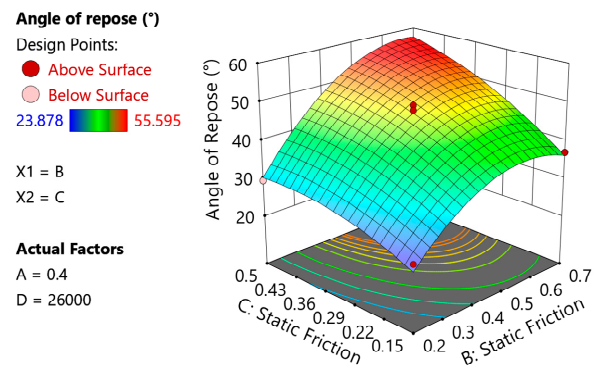
(c)



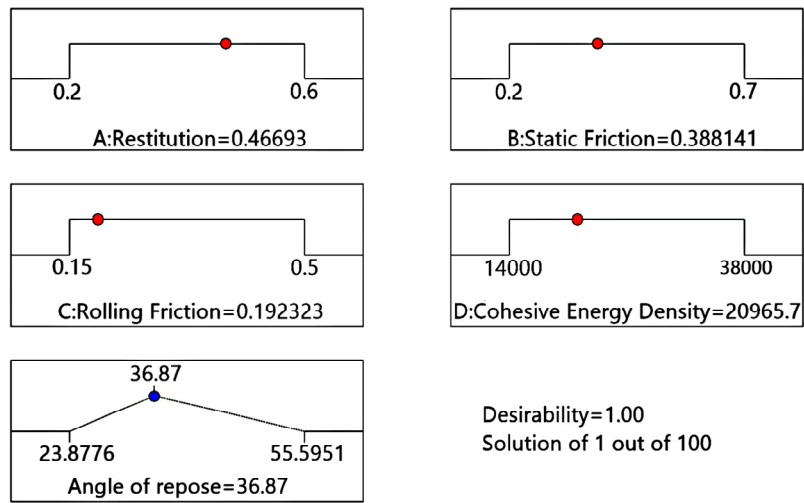
(d)



(e)



(f)



(g)

Supplementary Figure S4. DEM input parameter calibration for the clay soil: (a) static angle of repose test, (b) static angle of repose measurement using EDEMPy script, (c) normal plot of residuals, (d) predicted versus actual diagnostic plot, (e) static angle of repose 3D surface plot for rolling friction and static friction, (f) static angle of repose 3D surface plot for static friction and restitution, (g) numerical optimisation result.