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暴雨冲击下之坡地破坏及保护

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摘　要　以试验方法, 探讨暴雨作用下于不同坡度时, 对坡地破坏及保护方式之研究。保护方式分为 4 类: 地下排水、浅层排水、干砌卵石及浆砌卵石。试验中观测地下水之变化, 量测流失之土方、排水量, 以及最后破坏之断面, 并进行边坡稳定分析。试验结果指出: (1) 压实度较小、渗透性较佳之土壤, 因地下水渗透, 在坡脚产生瞬间坍方。(2) 压实度较大、渗透性较差之土壤, 将产生地表径流冲蚀, 若无排水或坡地保护措施, 将发展成严重的径流冲蚀, 造成坍方。
关键词　暴雨　坡地　试验　破坏

Side Slope Failure due to Storm and Its Protection

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Abstract　The main purposes for experimental studies are about the failure processes and types of slopes under the attack of heavy storm. The effects of protections by underground drainage, shallow depth drainage, mortarless cobble protection and mortar cobble protection to the slope stability are discussed. The variation or groundwater table, soil loss volume, drainage quantity and the last failure section are measured. At the same time, the stability of slopes by computer in order to obtain the smallest factor of safety is analyzed. The numerical calculation would support to the experimental results, which can not give the factor of safety in details. The test results show that: (1) For low degree of compaction and moderate permeability of soil, suddenly landslides will occur at toe of slope due to the seepage of groundwater. (2) For high degree of compaction and low permeability of soil, erosion by surface runoff will occur. Landslide, resulted from severe erosion of surface runoff will occur in the case of without drainage or without slope surface protection.
Key words　storm　side slope　experiment　failure

1　Introduction

The problems of slope failure are serious to railroad, highway and hydraulic aspects as well. The field data of situ measurement are few in the situation caused by heavy rain storm, on

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the other hand the analytical studies are based on ideal assumption, say, homogeneous and isotropic strata uniform size, etc. Therefore it is better to be done in the laboratory with the facility of artificial rainfall. According to the universal erosion formula, the erosion rate will depend on five factors, namely, the rainfall intensity, side slope, soil type, land use and hill-slope length. In the laboratory the first four factors can be reproduced in reality, not the fifth, but it can be solved in some degree (Liu and Hsu, 1990). The other factors are not included in the universal formula e.g. the compaction of soil, samples remodel and the soil depth, of course, which are of second importance in nature and still call be remedied.

These investigations are taken in the laboratory to lay emphasis on the engineering measure of drainage and protection. The drainage systems are provided in different arrangements middle drainage and bottom drainage under the ground in elevations with soft holed-pipes. Drainage works are regarded as fundamental measures for the side slope stability. If not enough, the protection works such as mortarless cobble work, mortar-cobble work, even retaining wall can be added to straighten the slope. All of them are tested under heavy storm in the laboratory.

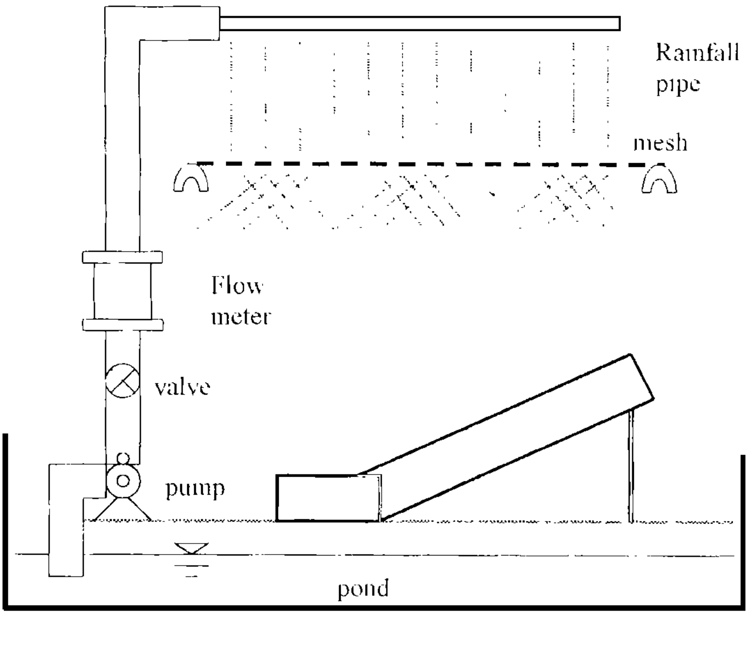

Fig 1 Artificial rainfall facility

2 Facility

The artificial rainfall set is 10 m long, 4.5 m wide and 3 m high and is made in steel structure. The main pipe is made of PVC, 7.5 cm in diameter and sub-pipes, 2.5 cm PVC are made with many holes, 10 cm each apart. Two holes, 0.8 mm in diameter, make the rainfall with 30° angles in direction to the vertical. Below them 50 cm in depth there are two layers of nylon mesh in order to redistribute the raindrops for evenly distribution. Three sets of them are responsible for upstream, midstream and downstream respectively. Each set has 5 HP electric motor and pump in operation. Floating type flow meters are placed in the pipes in order to measure the discharge. (Fig. 1)

The test case is 140 cm long, 80 cm wide and 30 cm high, with horizontal platform as the simulation to the road along hillside. The steel frame sustains the test case which can be adjusted its inclination.

3 Scopes and conditions of experiment

3.1 The experiment scope covers the following

(1) The test slopes are selected two: 30° and 45° inclinations.

(2) Bare soil without any measures are tested as a fundamental research for the natural condition.

(3) TAKADA pipes are used for drainage, with 50 mm and 80 mm different diameters, placed at the middle or bottom positions. (See Photo 1)

(4) Mortarless cobble work (See Photo 2) and mortar cobble work (See Photo 3) are used on the face of side slope for protection, each one of the cobbles is about 15 cm long and 10 cm wide. The coarse filter and the graded filter (See Photo 4) are occasionally added behind the cobble layer to make better drainage effect. The graded filter has to fulfill the following:

$$\frac{D_{15}(\text{filter})}{D_{85}(\text{soil})} < 5, \quad \frac{D_{15}(\text{filter})}{D_{15}(\text{soil})} > 5$$

(5) The combination of (3) + (4) may give better results.

(6) All experimental models are listed in Fig. 2.

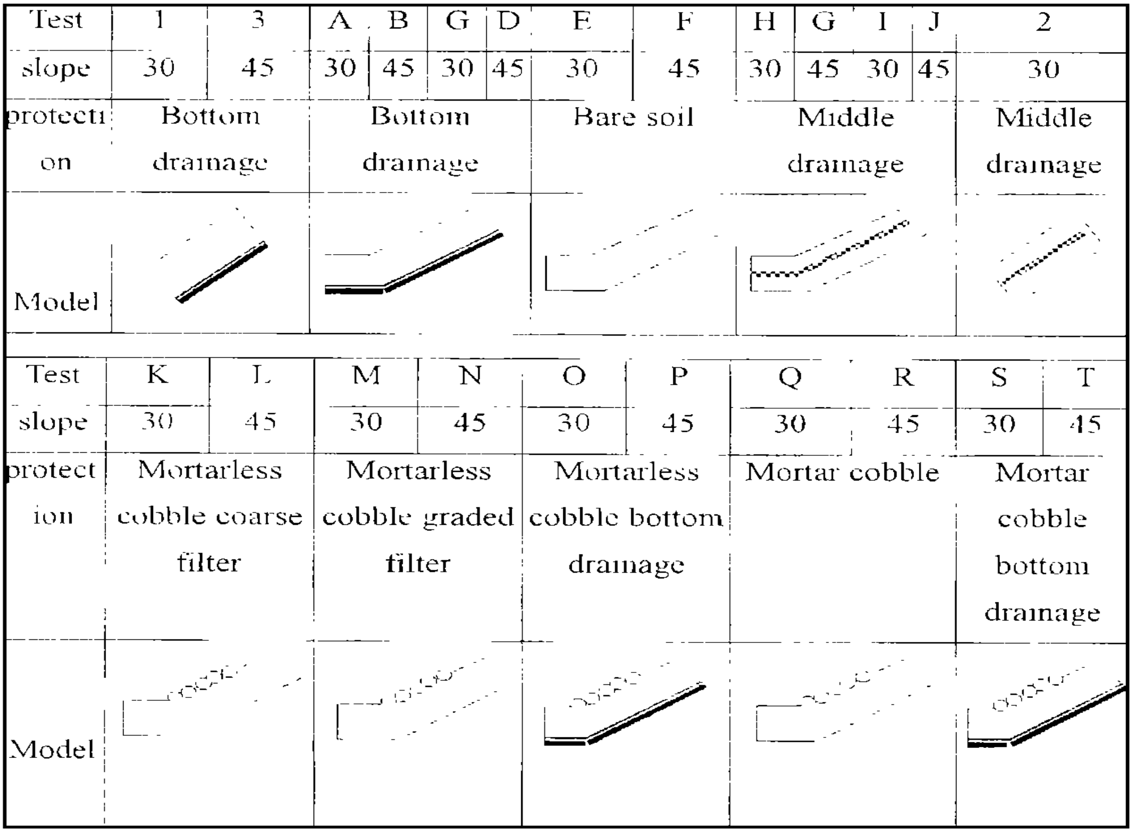

Fig2 Slope protection for test

3.2 The conditions of experiments are given as

(1) The rainfall intensity is selected at 150 mm/h (±) which is the largest in record and

the rainfall duration is 80 min, which may happen in reality.

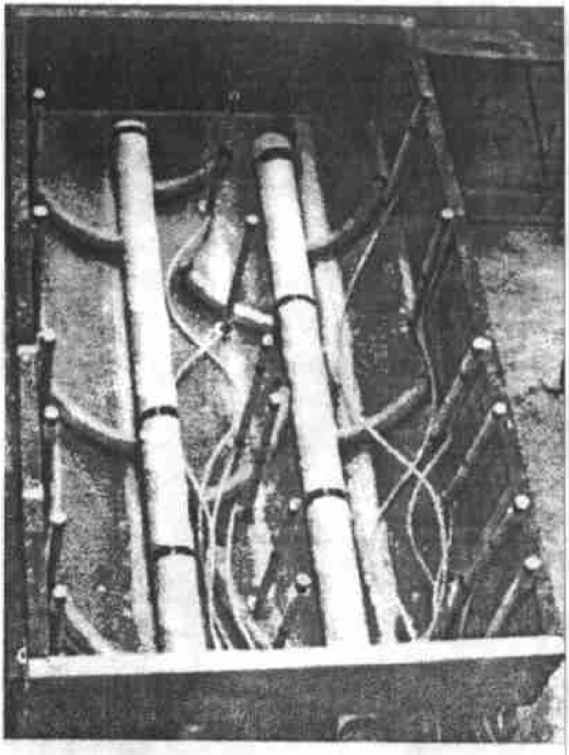

Photo 1 TAKADA pipe bottom drainage

Photo2 Mortarless cobble work

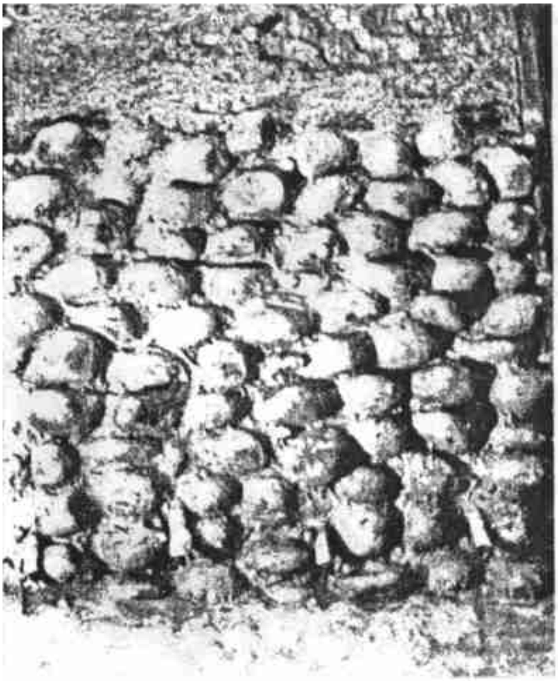

Photo3 Mortar cobble work

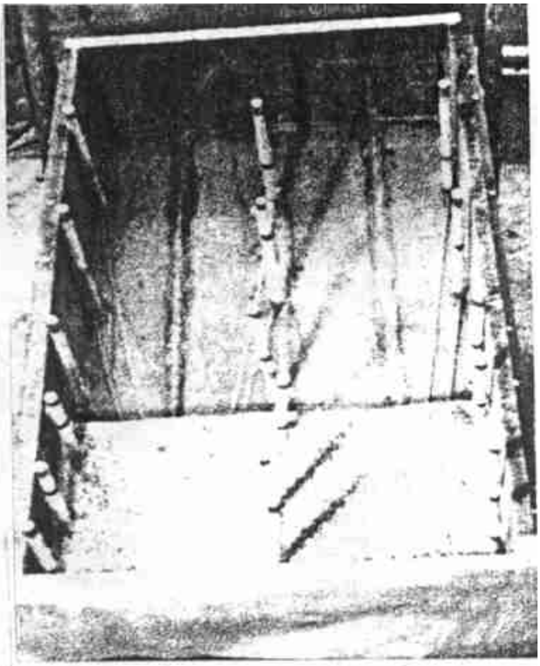

Photo 4 The graded filter

(2) The tested soil sample consists of 2% clay, 53% silt and 45% fine sand. It is a type of silty loam according Triangular Soil Classification, and belongs ML (low plastic silt) based on Unified Soil Classification.

Table 1 Distribution of diameters of tested soil

D10 mm	D30 mm	D60 mm	Cu
0.043	0.070	0.076	1.77

(3) The mean specific gravity of soil grains is 2.65. The dry unit weight of soil is 1.33 g/cm^3. Under constant head and variable head permeability test, the average figure of permeability coefficient K (20°) is 1.34×10^{-3} cm/s.

(4) From Atterberg Limit Test, the tested soil has LL= 24.0, PL= 22 and PI= 2.

(5) From Standard Proctor Compaction Test, the O.M.C. (optimum moisture content) is 16.1%. The maximum dry unit weight of soil $r_{d\max}$ = 1.662 g/cm^3. Then the degree or compaction for the tested soil is about 80%.

(6) From Direct Shear Test, the angle of internal friction is Φ= 35°, the cohesion is C = 0 for saturated case while Φ= 39°, C = 0.018 kg/cm^2 for wetted case.

(7) The conditions of experiment can be listed in Table 2.

Table2 Experiment conditions

Test No.	Slope (°)	Pipe diameter (mm)	Rainfall intensity (mm/h)	Rainfall duration (min)	Wet soil unit (g/cm^3)	Water content (%)	Dry soil unit (g/cm^3)	Compaction (%)
1	30	50	145	60	1.50	13.3	1.33	80
2	30	50	150	60	1.64	20.6	1.36	82
3	45	50	159	60	1.37	10.3	1.24	75
A	30	50	141	90	1.54	13.0	1.37	82
B	45	50	147	80	1.61	16.4	1.38	83
C	30	80	143	80	1.51	10.7	1.36	82
D	45	80	149	90	1.46	12.5	1.30	78
E	30	–	147	80	1.56	15.8	1.34	81
F	45	–	146	80	1.56	15.7	1.35	81
G	45	80	149	80	1.58	15.7	1.37	82
H	30	80	143	80	1.56	15.2	1.35	81
I	30	50	147	80	1.50	13.0	1.32	80
J	45	50	150	80	1.51	13.5	1.33	80
K	30	–	152	80	1.51	13.3	1.33	80
L	45	–	148	80	1.64	13.8	1.44	86
M	30	–	150	80	1.40	9.25	1.28	77
N	45	–	148	80	1.56	12.7	1.38	83
O	30	50	144	80	1.52	14.0	1.33	80
P	45	50	145	80	1.54	13.9	1.35	81
Q	30	–	153	80	1.49	12.6	1.32	80
R	45	–	147	80	1.42	13.0	1.26	76
S	30	50	148	80	1.40	11.3	1.26	76
T	45	50	143	80	1.53	12.4	1.36	82

4 Results and discussion

Under the attack of certain rainfall intensity and duration, the side slopes in 30° and 45° with different protections such as bottom drainage, middle drainage, mortarless cobble and mortar cobble have been tested in total of 23 runs. These results are summarized in Table 3 and analyzed in comparison as the following.

4.1 Compaction, permeability and erosion

The rain erosion to hill-slope will be different from soil type, land used, slope, length and rainfall intensity, and also depends upon the compaction and permeability of soil. In general speaking, the more compaction and the less permeability make more surface runoff, i. e. the serious erosion.

Table3 Experiment results

Test No.	Total drainage volume (ml)	First drain time (min)	First g. w. t rising time (min)	60 min v/v_o (%)	80 min v/v_o (%)	Finger erosion (min)	Rill erosion (min)	Mudflow (min)	Highest g. w. t. rising (cm)
1	–	–	38	7.7	–	35	40	55	14
2	–	–	43	20.8	–	10	15	55	9.3
3	300	–	41	39.3	–	none	none	45	6.3
A	15445	45	61	–	–	25	30	none	7.5
B	3630	50	36	5.5	9.3	10	30	none	12
C	6470	60	49	2.1	4.1	40	50	none	12
D	–	–	69	1.4	2.4	20	40	none	10.6
E	–	–	60	2.3	13.3	20	30	70	20
F	–	–	67	2.5	22.0	10	20	70	15.4
G	4305	30	58	6.9	15.5	10	20	70	10.6
H	3810	35	57	2.3	8.1	10	20	70	9.2
I	10105	50	50	2.8	12.4	40	50	70	13.8
J	6185	38	54	1.8	15.3	35	50	70	11.7
K	–	–	23	1.9	7.4	50	65	75	20.9
L	–	–	33	1.7	7.4	45	65	80	16.7
M	–	–	31	0	0	70	75	none	20.7
N	–	–	19	2.7	13.3	45	60	70	16.8
O	20470	18	21	0	0	35	75	none	22.3
P	18680	20	25	0	2.1	60	none	none	17.2
Q	–	–	28	0.2	1.1	35	65	none	18.2
R	–	–	25	0	0.1	60	none	none	14.4
S	1700	15	65	0	0.2	none	none	none	1.1
T	5680	20	45	0	0	45	none	none	13.3

(1) This experiments use the degree or compaction about 80% (75% for test run 3 only and 70% in previous investigation). In the case of low compaction, the rainfall nearly all infiltrates into soil. The soil moisture content rapidly increases and the shear resistance decreases, consequently the side slope will be unstable, firstly erodes at the toe and gradually extents to the whole slopes (See Test 3). The same results were obtained in previous studies on ground drainage, toe drainage, ditch drainage and vegetation cover.

(2) In case the compaction is little high (80%), the void ratio will be reduced and the permeability goes to low. From these experiments (except Test 3) the surface runoff produces after 10～20min when the rainfall commences, the top soil is attacked and carried away as from sheet erosion, finger erosion and finally rill erosion. The flowing, water and soil are mixed as mudflow. Tests (1), (2), (E), (F), (G), (H), (I), (J), (K), (L) and (N) all belong to such category of slope failure.

4.2 Slope and erosion

(1) From Table (4) and the highest groundwater table curves (Fig. (3) and (4) as illustrated in Test 11: mortarless cobble, Test(K) and(L); bottom drainage, test (C) and (D)), in the case of no drainage, the groundwater table or slope 30° is higher the one of 45°. If the drainage is provided, the two cases 30° and 45° of 45° have no significant difference. If having the same protection, the groundwater tables of slope 30° are all higher than the 45° one (Fig. 4).

Table4 Highest groundwater-slope

With Drainage	Test No.	1	2	3	A	B	C	G	H	I	J	O	P	S	T
	Slope(%)	30	30	45	30	45	30	45	30	30	45	30	45	30	45
	H(cm)	14	10.6	6.3	7.5	8.9	12	10.6	9.2	13.8	11.7	22.3	17.2	1.1	13.3

Without Drainage	Test No.	E	F	K	L	M	N	Q	R
	Slope(%)	30	45	30	45	30	45	30	45
	H(cm)	20	14.4	20.9	16.7	20.7	16.8	18.2	14.4

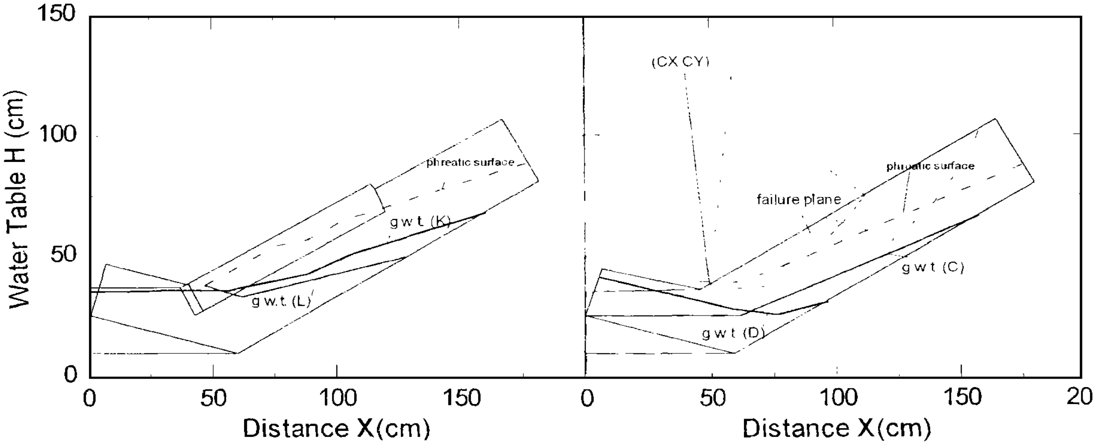

Fig3 Mortarless cobble highest g.w.t. for Test (K)(β= 30°)and Test (L)(β= 45°)

Fig4 Bottom drinage highest g.w.t. for Test (C)(β= 30°)and Test (D)(β= 45°)

Table5 Groundwater table(descent order) Slope: 45°

Order	Test No.	Protection	Failure pattern	Remark
1	F	bare soil	Z	1 g.w.t.(F.L.N.) nearly same
2	L	mortarless cobble coarse filter	Z	④no drainage
3	N	mortarless cobble graded filter	Z	
4	P	mortarless cobble bottom filter	X	1 g.w.t. lower than N ④g.w.t(toe higher than J's
5	J	middle drainage d= 50mm	Z	1 g.w.t.(J.G.) nearly same
6	G	middle drainage d= 80mm	Z	④diameter different
7	R	mortar cobble	X	1 g.w.t.(middle) lower than G's no drainage ④g.w.t.(toe) higher than G
8	B	bottom drainage d= 50 mm	Y	1 g.w.t(B.D.T.) nearly same
9	O	bottom drainage d= 80 mm	Y	④with drainage
10	T	mortar cobble bottom drainage	X	㈣g.w.t.(toe of T) is high

Slope: 30°

Order	Test No.	Protection	Failure pattern	Remark
1	K	mortarless cobble coarse filter	Z	1 g.w.t.(K.M) nearly same
2	M	mortarless cobble graded filter	X	④no drainage
3	E	bare soil	Z	1 g.w.t.(K.M.) nearly same
4	O	mortarless cobble bottom filter	X	④toe E> 0; middle E< 0
5	Q	mortar cobble	X	no drainage
6	I	middle drainage d= 50mm	Z	Toe 1> G> H
7	G	middle drainage d= 80mm	Y	Middle 1< G< H
8	H	middle drainage d= 80mm	Z	g.w.t(G.H.) nearly same
9	A	bottom drainage d= 50mm	Y	g.w.t. H> A> S
10	S	mortar cobble bottom drainage	X	Nearly no g.w.t.

Note: X: finger erosion or light rill erosion
Y: rill erosion
Z: mudflow

(2) From Table(5) under same protections with rainfall duration 80 min., the total loss volumes of soil in the case of slope 45° are nearly all greater than the 30°s one (F> E, G> H, J > I, L= K, N> M and P> 0) and a few exceptional cases (C> D, Q> R, S> T) with marginal differences only.

(3) Observing (1) and (2), the infiltration rate decreases as the slope increases. The 30°s case has higher infiltration rate and higher groundwater table, on the other land the 45°s case has less infiltration rate and more surface runoff, i.e. serious soil loss.

Table6 Total loss volume ratio types of protection　Slope: 45°; Time: 80min

Test No.	F	G	J	N	B	L	D	P	R	T
Protection	Bare soil	Middle drainage d= 80mm	Middle drainage d= 50mm	Mortarless cobble graded filter	Bottom drainage d= 50mm	Mortarless cobble coarse filter	Bottom drainage d= 80mm	Mortarless cobble bottom drainage	Mortar cobble	Mortar cobble bottom drainage
V/V_o (%)	22	15.5	15.3	13.3	9.3	7.4	2.4	2.1	0.1	0
Failure pattern	Z	Z	Z	Z	Y	Z	Y	X	X	X

Slope: 30°; Time: 80min

Test No.	E	I	H	K	C	Q	S	M	O
Protection	Bare soil	Middle drainage d= 50mm	Middle drainage d= 50mm	Mortarless cobble coarse filter	Bottom drainage d= 80mm	Mortar cobble	Mortar cobble bottom drainage	Mortarless cobble graded drainage	Mortarless cobble bottom drainage
V/V_o (%)	13.3	12.4	8.1	7.4	4.1	1.1	0.2	0	0
Failure pattern	Z	Z	Z	Z	Y	X	X	X	X

Table7 Capillary rise h_c

Test No.	i (10^{-3}cm/s)	k (10^{-3}cm/s)	e	n (%)	s (%)	v (10^{-3}cm/s)	Time at highest g·w·t (min)	h_0 (cm)
1	4.03	1.34	0.992	49.8	35.5	4.17	50	12.5
2	4.17	1.34	0.948	48.7	57.6	6.49	55	21.4
3	4.42	1.34	1.137	53.2	24.0	3.31	45	8.9
A	3.92	1.34	0.940	48.5	36.6	4.36	61	16
B	4.08	1.34	0.920	47.9	47.2	5.30	67	21.3
C	3.97	1.34	0.948	48.7	29.9	3.93	58	13.7
D	4.14	1.34	1.038	50.9	31.9	3.87	83	19.3
E	4.08	1.34	0.978	49.4	42.8	4.74	64	18.2
F	4.06	1.34	0.963	49.1	43.2	4.80	78	22.5
G	4.14	1.34	0.940	48.5	44.3	4.96	79	23.5
H	3.97	1.34	0.963	49.1	41.8	4.96	75	21.1
I	4.08	1.34	1.000	50.0	34.5	4.09	58	14.2
J	4.17	1.34	0.992	49.8	36.1	4.21	75	18.9
K	4.22	1.34	0.992	49.8	35.4	4.17	57	14.3
L	4.11	1.34	0.84	15.7	43.5	5.19	69	21.5
M	4.17	1.34	1.070	51.7	22.9	3.36	73	14.7
N	4.11	1.34	0.920	47.9	36.4	4.40	59	15.6
O	4.00	1.34	0.992	49.8	37.4	4.30	77	19.9
P	4.03	1.34	0.963	49.1	38.3	4.42	70	18.6
Q	4.25	1.34	1.001	50.0	33.4	4.02	80	19.3
R	4.08	1.34	1.103	52.4	31.2	3.72	78	17.4
S	4.11	1.34	1.103	52.4	27.1	3.51	–	–
T	3.97	1.34	0.949	48.7	34.6	4.21	77	19.51

(4) As shown in Table (6) and (7). The slope 45° without drainage and the middle

drainage are among the worst, while the protection with mortar cobble, and either the mortar cobble or the mortarless cobble with bottom drainage give the best solutions.

(5) As shown in Table (6) and (7). In the cases of slope 30° without drainage with middle drainage, are among the worst (M as exception only), while mortarless cobble with graded filter at toe, mortar cobble protection, and these two alternative with bottom drainage give the best results.

(6) Observing Table (7) slope 45° is more danger than the 30°s one, however, if treatment is provided in suitable way slope 45° will be greatly improved and can compare with the 30°s one.

4.3 Drainage, groundwater table and erosion

(1) From Table(6) and Fig. (5), (6) examining the Tests 45°(F), (B) and Tests 30° (K), (A), they show that the groundwater tables are among the highest for the cases of bare soil and mortarless cobble whatsoever slope 30° and 45° because not only infiltration can not be reduced on the surface and also the groundwater cannot be drained out. The collapse nearly all comes from surface runoff and the mudflow is generated.

(2) In the case of the mortar cobble work is provided at the lower part of the hill-slope. The rain infiltration can be stopped at this part and the bottom drainage is also used to drain the seepage of upper part out, then the groundwater table is little raised and the erosion is only slight (finger erosion).

(3) From Tests (B) and (L) listed in Table (6) and (7), the loss volume of (B) is comparative large, but the slope has only rill erosion due to low groundwater table. On the other hand (L) has high groundwater table and serious mudflow is produced at the toe. From this illustration the drainage effect is quite significant.

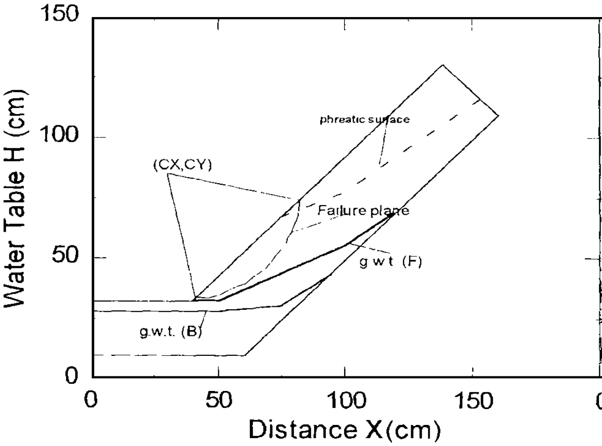

Fig5 Highest g.w.t.for Test(F) (Bare soil) and Test (B) (Bottom drainage) in $\beta = 45°$

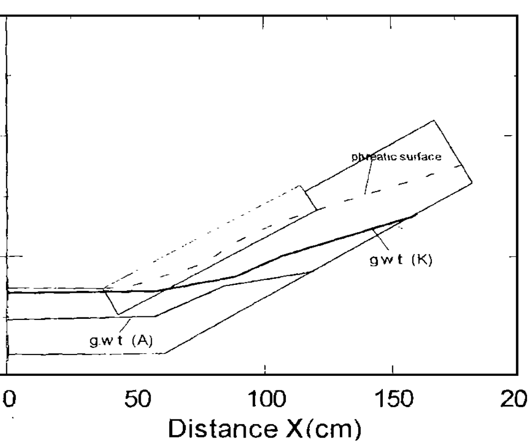

Fig6 Highest g.w.t.for Test(K) (Mortarless cobble, coarse filter) and Test(B) (Bottom drainage d= 50 mm) in $\beta = 30°$

(4) From Table(6), the situations with same slope and protection have about same g. w.

t. (groundwater table) as illustrated as Test (L) and (N), Test (J) and (G), TesT (B) and (D) and Test (K) and (M).

(5) The tested soil is silty loam and its grain is fine. The capillary flinge makes the saturation limit higher than g.w.t. From Table (8) it is possible to calculate the limiting rate of infiltration v through the formula $v = k/(1-s)^n$ where k, s, n, are coefficient of permeability, initial degree of saturation and porosity respectively. The phreatic surfaces are shown as dotted line through Fig. 3–6 where very about the same due to uniform compaction and homogeneity.

Table8 Time period-loss volume ratio

Slope: 45°

Test No.	Time	30	40	45	50	55	60	65	70	75	80	85	90
3	bottom drainage	0.2	0.2	1.7	17.8	33.0	39.3						
B	bottom drainage d= 50mm	1.0	1.7	2.2	2.9	3.7	5.5		8.4		9.3		
D	bottom drainage d= 80mm	0.5	0.6		1.0		1.4		1.4	2.1	2.4	2.5	2.8
F	bare soil	1.3	1.6		2.1		2.5		5.5	17.2	22		
G	middle drainage d= 80mm	1.8	2.4		4.3	4.3	6.9	8.0	9.6	12.3	15.5		
J	middle drainage d= 50mm		0.4				1.8	3.1	6.3	10.1	15.3		
L	mortarless cobble coarse filter						1.7	2.9	4.6	6.4	7.4		
N	mortarless cobble graded filter				1.3		2.7	4.7	6.9	10	13.3		
P	mortarless cobble bottom drainage						0		0.8		2.1		
R	mortar cobble						0				0.13		
T	mortar cobble bottom drainage						0				0		

Slope: 30°

Test No.	Time	30	40	45	50	55	60	65	70	75	80	85	90
1	bottom drainage	0.4	0.9	2.5	4.4	6.1	7.7						
2	middle drainage	4.6	7.4	9.5	12.7	16.1	20.8						
A	bottom drainage d= 50mm												
G	bottom drainage d= 80mm					1.5	2.1	3.6	2.4	2.6	4.1		
E	mm bare soil	1.1	1.5		1.8		2.3		6.0	9.3	13.3		
H	middle drainage d= 80mm	1.0	1.4		1.9		2.3	4.6	3.3	5.1	8.1		
I	middle drainage d= 50mm	0.6			1.2		2.8		6.3	9.0	12.1		
K	mortarless cobble coarse filter				0.6		1.9	2.8	3.9	5.5	7.4		
M	mortarless cobble graded filter										0		
O	mortarless cobble bottom drainage						0				0		
Q	mortar cobble						0.2				1.1		
S	mortar cobble bottom drainage						0				0.2		

4.4 Protection, soil loss volume

According to Table(7), the following results can reach:

(1) The case of bare soil without any protection has the most serious damage and soil loss volume, starting from the toe up to the slope. The reason is that the slope without protection is directly attacked by rainfall and the soil texture is decomposed. The rills are deepen and widen through grinding and washing (Photo. 3) the rising groundwater can not be dreamed out, making cohesion and angle of internal friction decrease, the g.w.t. flow can carry the finer or soil away so as "under ground erosion".

(2) The protection or mortarless cobble work is not all successful when $\beta = 45°$. Since the slope is steep and g.w.t. is high (Table 6) the fine sand and silt under cobble layer will be

washed out and the cobble will sunk down making slope unstable. On the other hand, the mortar cobble work is effective, however the loss volume is reduced to minimum if bottom drainage is provided. The motor cobble work not only eliminates the infiltration, but also reduces the length of slope. In the case of 30°, the effectiveness of mortarless cobble work depends on graded filter, which can prevent the fine sand and silt away. If only coarse filter, not graded, is used the work is not effective. Mortar cobble work gives good results on both loss volume and erosive damage.

(3) For drainage system, in the case of bottom drainage work has slight loss volume and erosive damage whatever 30° and 45°, however mortar cobble work is still the better one. The bottom drainage makes quick drainage and lowing or groundwater. The middle drainage is not good one in view of the loss volume and erosive damage, only better than the case or bare soil, for its poor drainage ability.

(4) The relationship between loss volume and time is established as Fig. 7 and Fig. 8 based on Table(9). The Test 3 is some different from the others for its low compaction. At the time

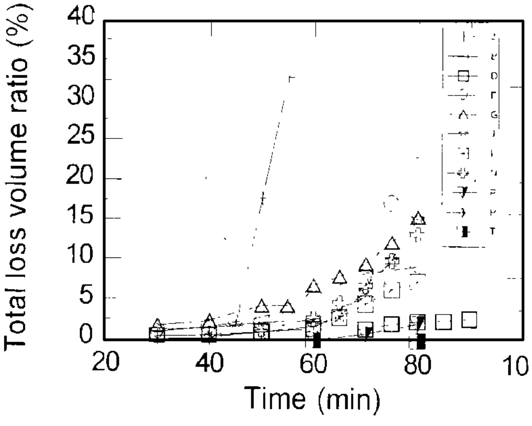

Fig7 Relationship between total loss volume ratio and time($\beta = 45°$)

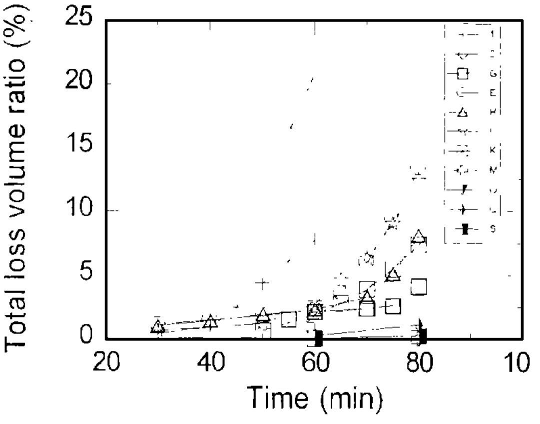

Fig8 Relationship between total loss volume ratio and time($\beta = 30°$)

of 45 min, after rain commencement, only small soil loss happens, because nearly all rainfall infiltrates into the soil. The soil moisture content continuously increases and the g.w.t. rises. The slope is rapidly collapsed at the toe and extends to the up side. A great soil loss happens, the same is the bare soil case. If there are surface protection and bottom drainage to be added, only small erosions such as finger erosion or rill erosion can be seen. Tests (G), (J), (N), (B) and (L) have the same trend or loss volume. They have different quantity in accordance with tile way of protections, and they are getting bigger as the rainfall duration increases. In Fig. 8 Tests (1) and (2) are under same experimental condition, however with different drainage condition (say, bottom and middle drainage), the loss volumes for the two tests have little different results. It can be seen that the middle drainage is not effective and so the loss volume is great. In the slope 30°, a gentle inclination has less loss volume if the surface protection and/or bottom drainage is used. For the rest, the loss volume will increase as the rainfall duration increases however slight difference in accordance with the slopes and protection.

Table9 Minimum factor of safety

Test No.		Slope: 45°					Slope: 35°				
		B	D	F	G	J	B	D	F	G	J
Before rainfall F. S.		1.078	1.078	1.078	1.078	1.078	1.600	1.600	1.600	1.600	1.600
Before rainfall F. S	g. w. t	0.964	0.967	0.965	0.965	0.966	1.434	1.434	1.435	1.435	1.436
	Phreatic surface	0.478	0.525	0.150	0.225	0.387	1.130	1.152	0.655	0.744	1.123

4.5 Profile damage

As the slope failure and mudflow produced, the surface of damaged profile is curved and called "Toe Failure Type". The tested soil is remolded and is relatively homogeneous, in computer analysis later the slip circle is assumed as the failure plane.

4.6 Computer analysis

The computer program is rewritten according to Bishop's Modified l-Method (Bowles 1974). As above said in 5 on such assumptions the electronic computations to test A through J are done on the factor of safety in cases: before rainfall and after rainfall. The 24th circle centers of failure plane are tried to find then the minimum factors or safety of them are the possible slip planes (Fig. 4 and 5).

It can be seen from the analyzed results:

(1) From Table 10 the slip plane is shallow slip, not to reach g. w. t, the factors to stability are angle of internal frictional Φ, unit weight r_m and slope β etc. The tested soil belongs to the same type and has no significant difference in properties of physics and mechanics. Therefore the values of factor of safety of tests are close together if considering only the highest g. w. t. in observations.

(2) The capillary phenomenon exists owing to fine grains of tested soil. The saturation limit is raised since then, consequently the stability will be reduced and F. S. values in Table (9) reflect this effect.

(3) Test (E) and (F) are the cases or bare soil, the F. S. are among the lowest. The cases of middle drainage have little high F. S. figures in (G), (J) and (H), (I). The cases of bottom drainage have the highest F. S. values such as (B), (D) and (A), (C). These results confirm the experiments of loss volume and damage pattern listed in Table (7).

5 Conclusions

(1) For the soil with low compaction and high permeability (silty loam), the seepage from groundwater makes quick displacement at the toe due to softened soil and results slope slide from bottom to top. The drainage of groundwater must be effective to avoid the rapid rise of groundwater table to get rid of collapse.

(2) For the soil with high compaction and low permeability (silty loam), the slope collapse is mostly due to surface runoff erosion, starting from finger erosion and gradually larger

enough to slope slide, still smaller than the case or seepage. Therefore the measure of surface drainage must be taken in order to prevent serious erosion happening on the slope.

(3) As the slope is concerned, the groundwater table of the slope 30° is higher than the 45° one having same protections no matter how with or without drainage. The slope 45° has greater soil loss volume than the 45° one at same protection condition, because of surface runoff and erosive damage.

(4) The slope 45° one has the most erosive damage if no drainage or only middle drainage are provided, on the other hand the mortar cobble work at the toe with bottom drainage having only slight erosion is the best one. Therefore the steep slope has to be protected at hill toe against surface flow. In the mild slope as 30° the bare soil and middle drainage are among the worst in erosive damage, if mortarless cobble work used for protection, the graded filter is the key to success. Mortar cobble work, mortarless cobble work with graded filter or bottom drainage has good results. In general the slope 45° are more dangerous than the 30° one, but the 45° one with suitable treatment may be better than the 30°'s one without any treatment.

(5) As groundwater table is concerned the slope hill without drainage has the highest level and serious mudflow is generated, while the mortar cobble work with bottom drainage give the lowest g.w.t., then the erosive damage is very light.

(6) As protection is concerned, the bare soil has no protection and is caused the most serious damage. The mortarless cobble work to steep slope, say 45°, is ineffective, but it has good results in slope 30° if graded filter is provided. The mortar cobble work is good, whatever slope 30° and 45°, and it gives the best results if bottom drainage is used. As drainage is concerned, the bottom drainage ranks the first and the middle drainage plays no role. The protection at toe with bottom drainage makes the best.

(7) In the stability analysis, the F.S. values based on observing data from experiments are quite close. In consideration of the fine grain in soil making capillary rise, the bare soil case gives the lowest F.S. i.e. the worst one, middle drainage little better, and bottom drainage the best. This computation confirms with the experiment, where the up capillary rise in fine soil must be taken into account in slope stability analysis.

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