TGS Geotechnical Lecture:

THE BASIC PROPERTIES OF MUDSTONE SLOPES IN SOUTHWESTERN TAIWAN

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ABSTRACT

The mudstone in the southwestern Taiwan is lithified shortly and is poorly cemented. Water absorption in the rocks results in swelling, slaking, and weakening. Hence, ground erosion, sliding of weathered layer and mud flow are noticeable geological hazards at the mudstone slopes. This paper reviews available literature regarding the distribution and basic properties of mudstone. In addition, we briefly describe the characteristics and geological disasters at mudstone slopes. Furthermore, the precipitation and temperature data in Tainan and Kaohsiung show the approaching of global warming to the mudstone area. This study is expected to assist the researchers to simply understand the characteristics of mudstone and mudstone slope to continuously investigate new methods to mitigate the local disasters.

Key words: Mudstone, slope, Ku-ting-keng formation, property, southwestern Taiwan.

1. INTRODUCTION

The mudstone formation exposed in the foothills area of southwestern Taiwan is a sedimentary rock formed in the end of the Tertiary Period to the initial of the Quaternary Period. The mudstone formation distributes more than 100,000 hectares, and mainly generates the slopelands in Tainan and Kaohsiung counties.

The mudstone is lithified shortly and cemented poorly. It behaves as a rock in dry condition, but performs swelling, slaking and softening under an environment full of water. Hence, the slope damages, such as slope surface erosion and slope failure, occur frequently in this mudstone area during a rainy season. Consequently, the badland topography, like the landscape in the Moon, can be observed at some regions in the mudstone area.

Since a heavy rainfall can often induce the slope failure, slope surface erosion, and mud flow, the mudstone area in southwestern Taiwan becomes a visible geological hazard area.

Moreover, the global warming promotes a strong disturbance on the world-wide weather. Subjecting to the impact, both of the rainfall pattern and environmental temperature in the mudstone area are changing obviously. The number of high temperature day is increasing, the rainy season is gradually shortened, but the intensity of heavy rain usually renews its record. Thus, the mudstone area in southwestern. Taiwan now is under a very serious situation which it has never been subjected.

To overcome the geological hazards frequently occur in the mudstone area using suitable engineering protection methods and avoid the new impact of global warming, it is essential to fully understand the basic properties of mudstone and mudstone slopes, as well as, the changes in the environment, such as temperature and precipitation, in southwestern Taiwan.

Manuscript received November 20, 2007; accepted November 20, 2007.

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2. DISTRIBUTION OF MUDSTONE

In Taiwan, mudstone formation mainly exposed in three areas, which are the foothills area in southwestern Taiwan, the southern edge of the Coastal Range in Taitung, and the locations around Kenting in the Hengchun Peninsula. Among the mudstone areas, the one located at the foothills area in southwestern Taiwan (southwestern mudstone area) is spread the most extensively and near the urban area. It distributes from Chiayi county to Kaohsiung county and almost covers over the foothills areas of Tainan and north part of Kaohsiung. The eastern boundary of the mudstone area from the north is Kuang-zu-ling, Bei-liao, Yu-jin, Nan-hua, Nei-men till the south edge at Chi-shan. On the other hand, the villages on the western boundary are Liou-jia, Kuang-tien, Da-nei, Shan-shang, Shin-hua, Kuang-miou, Tien-liao, and Gang-shan. The main part of the mudstone area is also located at the western side of the upper stream of the river Tseng-wen-si and the river Chi-shan-si. The total area of this mudstone area includes over 100,000 hectares. Photo 1 shows a typical bared surface of mudstone slope, and photo 2 displays the topographical feature of the mudstone slope land taken from the top of Height 308 at the border of Tainan and Kaohsiung.

In 1933, the Japanese Geologist K. Torii (1933) investigated the petroleum geology in the southern part of Taiwan, he named the mudstone series as Ko-te-ko formation. Now, the Japanese character of Ko-te-ko formation is pronounced with Taiwanese by Ku-ting-keng formation.

Ho (1997) pointed out that the total thickness of the Pliocene rocks exceeds 3,000 meters in southern Taiwan, and in a few places, small limestone lenses are intercalated in the mudstone, varying from 2 to 20 meters thick. In the south of the river Tseng-wen-si, the Pliocene sediments characterized as a dark

Photo 1 A typical bared mudstone slope

Photo 2 The topographical feature of mudstone slopeland (from the top of Height 308)

gray mudstone series were called the Ku-ting-keng formation in old literature. The lowest part of this mudstone series might be overlapped into the Upper Miocene. Figure 1 illustrates the rock types and thickness of Pliocene stratigraphies of the western foothills (Ho 1997). The thickness of the mudstone series in Tainan and Kaohsiung area attains to 5,000 meters. And Table 1 shows the sequence of Neogene and Pleistocene rocks in the western foothills (Ho 1997).

Keng (1981) investigated the geology of the hills at the eastern Tainan, he renamed the Ku-ting-keng formation as Nan-hwa mudstone and defined the distribution area as from Yu-jin as the north boundary to Yen-chao as the south limit. The length of this area reaches 35 km, the width of the east-west direction is about 8 km, and the total area approximates 280 km^2. Finally, the detail distribution of mudstone formation around Tainan and Kaohsiung is shown in Fig. 2, which was redrawn and finished by Chen (1985).

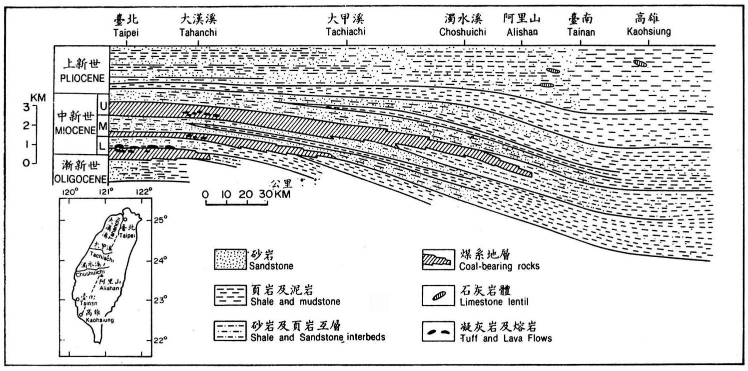

Fig. 1 The rock types and thickness of Pliocene stratigraphies in the western foothills (Ho 1997)

Table 1 Correlation chart of Neogene and Pleistocene rocks in the western foothills (Ho 1997)

<table>
<tr><td rowspan="2" colspan="2">area / age</td><td>South-central Taiwan</td><td colspan="3">Southern Taiwan</td></tr>
<tr><td>Chia-yi, Tainan</td><td>Tainan, Kaohsiung</td><td colspan="2">Kaohsiung, Pingtung</td></tr>
<tr><td rowspan="2" colspan="2">Pleistocene</td><td>Liu-suang formation
Erh-cung-ci formation
Kan-hsiao-liao formation</td><td>Yü-ching shale</td><td colspan="2">Liu-shuang formation
Liu-keui conglomerate</td></tr>
<tr><td rowspan="2">Liu-chung-chi formation
Yun-shui-chi formation</td><td rowspan="2">Pei-liao shale
Chu-tou-chi formation</td><td rowspan="3">Ku-ting-keng formation</td><td>(narrow sense)
Ku-ting-keng formation</td></tr>
<tr><td rowspan="2" colspan="2">Pliocene</td><td>Nan-shih-lung sandstone</td></tr>
<tr><td>Niao-tsui formation
Chung-lun formation</td><td>Mao-pu shale
Ai-liao shale
Yen-shui-keng shale</td><td>Kai-tze-liao shale</td></tr>
<tr><td rowspan="5">Miocene</td><td rowspan="2">Late</td><td>Tang-en-shan formation</td><td>Tang-en-shan formation</td><td colspan="2">Wu-shan formation</td></tr>
<tr><td rowspan="2">Nan-chuang formation</td><td rowspan="2">Chang-chih-keng formation
Hung-hua-tze formation
San-min shale</td><td rowspan="4" colspan="2"></td></tr>
<tr><td rowspan="2">Middle</td></tr>
<tr><td>Ta-pang formation</td><td rowspan="2"></td></tr>
<tr><td>Early</td><td></td></tr>
</table>

3. THE WEATHER IN SOUTHWESTERN TAIWAN

The records of temperature and precipitation in the south-western mudstone area must be reviewed and be investigated firstly to understand the influence of weather condition on the occurrence of natural geological hazards in this area. Since most of the mudstone formation distributes in Tainan and Kaohsiung counties, the weather records of these two counties can be adopted as the representative data for the mudstone area.

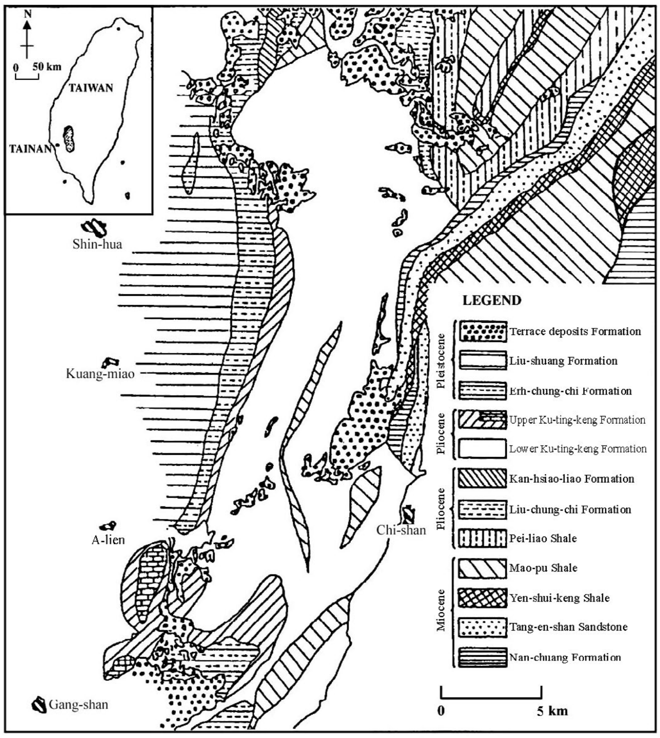

Fig. 2 The distribution of the rocks in southwestern mudstone area (Chen 1985)

According to the temperature and rainfall data, from 1971 to 2006, offered by the Central Weather Bureau (CWB) of Taiwan, the monthly average of the temperature and precipitation in Tainan and Kaohsiung are presented in Tables 2 to 5. In each table, the data was calculated for three different periods, the first column lists monthly average accumulated from 1971 to 2000, the second column shows the average value for each mouth from 2001 till 2006, and the third column presents the monthly average for the period of 1971 to 2006. The average monthly rainfall, from 1971 to 2000 and from 2001 to 2006, is also plotted with bar charts in Figs. 3 and 4 for Tainan and Kaohsiung, respectively.

Figures 3 and 4 indicate that the rainy season in the southwestern Taiwan starts from April till September, and more than 90% of the yearly precipitation concentrates in the wet season. And only 10% of the rain falls in the dry season, from October to March.

Based on Tables 2 and 4, during 1971-2000, the average yearly rainfall of Tainan and Kaohsiung are 1,672.4 mm and 1,784.9 mm, respectively. However, after twentieth century, the average yearly values are increasing to 1,723.5 mm in Tainan and 1,871.1 mm in Kaohsiung. Additionally, the rainy season is gradually shortening from half a year to five months, *i.e.* from May to September.

Oppositely, in Table 3, the average monthly temperature in Tainan was 24.1°C for the period of 1971 to 2000, and it rose up to 24.7°C during the first six years in 21th century. As well as the highest value of monthly average temperature is changed from 28.9°C (1971-2000) to 29.4°C (2001-2006). The similar phenomenon of temperature ascending can also be observed in Kaohsiung from Table 5.

Table 2 Monthly average precipitation in Tainan

Month	Monthly average precipitation in Tainan (mm)		
	Monthly average of 1971-2000	Monthly average of 2001-2006	Monthly average of 1971-2006
Jan.	19.9	20.1	19.9
Feb.	28.8	11.9	26.0
March	35.4	30.0	34.5
April	84.9	69.5	82.3
May	175.5	215.5	182.2
June	370.6	494.6	391.3
July	345.9	410.9	356.7
Aug.	417.4	218.5	384.3
Sep.	138.4	194.7	147.8
Oct.	29.6	13.5	26.9
Nov.	14.7	14.0	14.6
Dec.	11.3	30.5	14.5
Total	1672.4	1723.5	1680.9

Table 3 Monthly average temperature in Tainan

Month	Monthly average temperature in Tainan (°C)		
	Monthly average of 1971-2000	Monthly average of 2001-2006	Monthly average of 1971-2006
Jan.	17.4	17.9	17.4
Feb.	18.2	19.3	18.4
March	21.0	21.3	21.1
April	24.5	25.3	24.7
May	27.1	27.9	27.2
June	28.4	28.6	28.5
July	28.9	29.4	29.0
Aug.	28.4	29.3	28.5
Sep.	28.0	28.4	28.1
Oct.	25.9	26.3	25.9
Nov.	22.4	23.6	22.6
Dec.	18.7	19.5	18.9
Average	24.1	24.7	24.2

Table 4 Monthly average precipitation in Kaohsiung

Month	Monthly average precipitation in Kaohsiung (mm)		
	Monthly average of 1971-2000	Monthly average of 2001-2006	Monthly average of 1971-2006
Jan.	20	20.4	20.1
Feb.	23.6	10.2	21.4
March	39.2	11.1	34.5
April	72.8	39.8	67.3
May	177.3	265.1	191.9
June	397.9	444.1	405.6
July	370.6	466.9	386.6
Aug.	426.3	258.5	398.3
Sep.	186.6	269.3	200.4
Oct.	45.7	22.7	41.9
Nov.	13.4	19.5	14.4
Dec.	11.5	43.4	16.8
Total	1784.9	1871.1	1799.3

Table 5 Monthly average temperature in Kaohsiung

Month	Monthly average temperature in Kaohsiung (°C)		
	Monthly average of 1971-2000	Monthly average of 2001-2006	Monthly average of 1971-2006
Jan.	18.8	19.6	18.9
Feb.	19.7	20.9	19.9
March	22.3	22.6	22.4
April	25.2	26.1	25.4
May	27.2	28.1	27.3
June	28.4	28.4	28.4
July	28.9	29.3	29.0
Aug.	28.3	29.1	28.4
Sep.	27.9	28.1	27.9
Oct.	26.4	26.8	26.5
Nov.	23.4	24.5	23.6
Dec.	20.2	20.8	20.3
Average	24.7	25.3	24.8

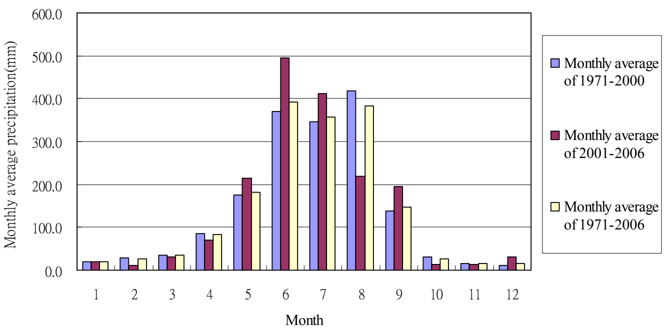

Fig. 3 Monthly average precipitation in Tainan (mm)

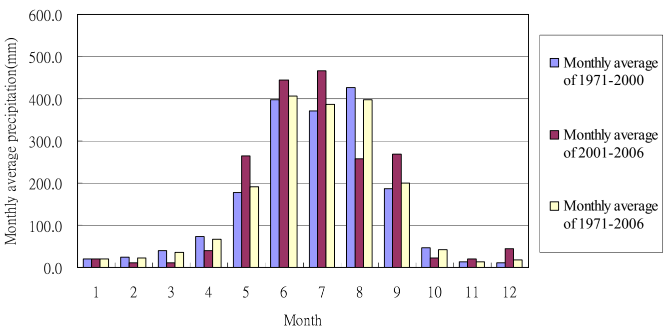

Fig. 4 Monthly average precipitation in Kaohsiung (mm)

As a result, the last six years records of rainfall and temperature in Tainan and Kaohsiung indicate that the global warming has already influenced on the weather situation of the southwestern mudstone area. The rising of temperature and the concentration of heavy rain fall will induce more serious damage on a slopeland of mudstone.

4. BASIC PROPERTIES OF MUDSTONE

In addition to the environmental factors, the geological hazards happened in the slopelands of mudstone are strongly governed by the basic properties of mudstone itself. In this section, the basic characters of mudstone, such as (a) physical properties, (b) chemical properties, (c) swelling, slaking and permeability, and (d) strength, will be discussed in detail as follows.

4.1 Physical Properties of Mudstone

Adding some new testing results of physical properties of mudstone on the data base collected by Hsu *et al*. (2003), the specific gravity (Gs), void ratio (e), water content (w), Atterburg's limits (LL, PL), plastic index (PI) and particle distribution, *etc*. of mudstone specimens sampled from the north (Tong-shan, Tainan) to the south (Chai-shan, Kaohsiung) of mudstone area, are listed in the Table 6.

The specific gravity of mudstone, scatters in the interval of 2.71-2.75 (Table 6), does not vary from different sampling places. However, the data of water content exhibits obvious difference between the Yu-jin sample and Chi-shan sample. The sample preservation condition after it was picked up from field affects the water content. The highest water content in Table 6 is 17.4%. Thus, the natural water content in mudstone formation is near to the value of 17%.

The liquid limit and plastic limit distribute from 29.0% to 42.2% and from 7.4% to 25.4%, respectively. The plastic index scatters in the interval of 10.5% to 24.8%, but most of them concentrate on a narrow range of 14% to 18%. The test results show that the mudstone is a material with low plasticity.

The final column presents the particle distribution of each mudstone sample by three kinds of particle content, sand (S), silt (M), and clay (C). There is an interesting phenomenon can be found in the relation between the sand particle content and the location of sampling. The mudstone sample picked up from the north part of the mudstone area has higher sand particle content than that sampled from the south part. This finding indicates that the original material of the mudstone formation was brought from the north of this area, and the sedimentation direction might also be from north to south. Hence, it is reasonable that only a few percentages of sand particles involved in the mudstone sample drilled from the south part of mudstone area. In spite of the difference in sand particle content, the silt content of each mudstone sample is more than 55%, therefore, all of the mudstone materials can be classified into CL-ML or CL by the Unified Soil Classification System.

4.2 Chemical Properties of Mudstone

Many researchers had put their efforts on analyzing the chemical characters of mudstone, such as chemical composition, mineral contents, pH value and the leaching substances from mudstone. The analysis results of the chemical properties will be introduced as follows:

(a) Chemical compositions of mudstone

During the period of Japanese colony, Lin (1943) had already taken a series of chemical composition analyses in the mudflow flooded from Mud-volcanoes. Recently, Lin *et al.* (1996) and Liao (2004) investigated the composition of mudstone, sampling from Chi-shan and Tien-liao, respectively. Table 7 lists all of the results and shows that the most important composition in mudstone is SiO_2, and then, $Al_2O_3 \cdot Fe_2O_3$, and the mudstone also contains several percent of CaO or MgO.

Table 6 Physical properties of mudstone (Hsu and Liu 2003; Lee *et al.* 2005)

Sampling place	*Gs*	*e*	*w* (%)	γ_d (t/m^3)	Atterberg's limits (%)		Plastic index (%)	Particle distribution (%)			Reference
					LL	PL		S	M	C	
Tong-shan	2.73	–	17.0	1.90	42.2	25.4	16.8	10.0	55.0	35.0	Lee (2005)
Wu-shan-tou	2.75	–	17.0	(2.17)	37.0	21.0	16.0	10.0	65.0	25.0	Yang (1975)
Yu-jin	2.71	0.47	17.4	1.86 (2.18)	31.6	17.1	14.5	5.0	79.2	15.8	Juang (1976)
Kuang-miou	2.73	–	–	–	32.2	7.4	24.8	6.0	78.0	16.0	Lin (1975)
Long-chi	–	0.24	–	2.23	31.4	20.9	10.5	2.0	70.6	27.6	Hsieh (1995)
Tien-liao	2.71	–	–	2.24 ~ 2.26	41.0	23.0	18.0	1.1	56.9	42.0	Yeh (1999)
Chi-shan	2.71 ~ 2.72	0.22 ~ 0.27	1.73 ~ 2.00	2.14 ~ 2.24	28.2 ~ 30.3	16.0 ~ 18.8	–	6.0	64.0	30.0	Hsu (1999)
Chai-shan	2.72	–	–	–	35.1	20.4	14.7	4.0	65.7	30.3	Chen (1997)

*** (1 t/m^3 = 10 kN/m^3)**

Table 7 Chemical compositions of mudstone (Lin 1943; Lin *et al.* 1996; Liao 2004)

Sampling place	Chemical compositions	Reference
Gun-sheui-ping Mud-volcano	SiO_2 (63.49%)、$Al_2O_3 \cdot Fe_2O_3$ (21.53%)、CaO (2.71%)	Lin (1943)
Chi-shan	SiO_2 (48.27%)、Al_2O_3 (17.23%)、CaO (6.04%)、Fe_2O_3 (5.90%)、K_2O (4.67%)、Na_2O (4.25%)、MgO (2.72%)、CuO (0.39%)、SrO (0.09%)、MnO (0.06%)、ZnO (0.05%)、NiO (0.02%)	Lin *et al.* (1996)
Tien-liao	O (49.41%)、Si (25.57%)、Al (9.14%)、Fe (5.91%)、C (3.29%)、K (2.96%)、Mg (1.27%)、Ca (1.08%)、Na (0.81%)、Ti (0.56%)	Liao (2004)

(b) Mineral contents of mudstone

Table 8 shows the analytic results of mineral contents in mudstone, investigated by Tsai (1984a) and Lin *et al*. (1996). In addition to quartz and clay minerals, such as illite, chlorite, Kaolinlite, the minerals in mudstone included small amounts of calcium aluminate hydrate, ($CaO \cdot Al_2O_3 \cdot 10H_2O(CAH_{10})$) and calcium silicate hydrate ($1.5CaO \cdot SiO_2 \cdot XH_2O$, CSH). And, Lin *et al*. also pointed out that the CAH_{10} acts as a binding agent of the particles in mudstone. Furthermore, Tsai (1984a) also indicated that most of the clay mineral is illite (30.54%), and only a few percentages of Kaolinlite and swelling clays.

(c) pH value

Tsai (1984b), Yen *et al*. (1985) and Lee *et al*. (1994) performed pH value tests for the mudstone samples, which picked up from Si-zu-wan and Kaohsiung county. Lin (1997) checked the pH value for the mudflow flooded from Mud-volcanoes in Wu-shan-ting and Gun-sheui-ping. Table 9 lists all of the results of pH value tests and shows that the pH values of both mudstone and mudflow are about 8 to 9. Thus, the mudstone behaves as a slightly alkali material, and the sedimentary environment of mudstone formation might be concerned as a sea basin.

(d) Leaching substances from mudstone

Hsu *et al*. (1999) observed some white color crystals distributed on a mudstone slope surface after rainfall. They checked the crystal with the instrument of X-ray diffractometry (XRD), and identified that the crystal was Na_2SO_4.

Lin *et al*. (1996) also investigated the leaching substances from the mudstone picked up from Chi-shan, and found out the amount of dissolved ions with the sequence as

Table 8 Mineral contents of mudstone (Lin *et al.* 1996; Tsai 1984a)

Sampling place	Mineral contents of mudstone	Reference
Southwestern Taiwan	quartz (28.45%)、illite (30.54%)、chlorite (28.70%)、calcite (4.52%)、kaolinite (2.81%)、feldspar (about 5%)、swelling clays (few %)	Tsai (1984a)
Chi-shan	quartz、illite、calcium aluminate hydrate (CAH_{10})、calcium silicate hydrate (CSH)	Lin *et al.* (1996)

Table 9 pH value of mudstone (Yen and Tsai 1985; Lee *et al.* 1994; Lin 1997; Tsai 1984b)

Sampling place	pH value	Reference
Southwestern Taiwan	8.7 (upper Ku-ting-keng formation) 8.6 (lower Ku-ting-keng formation)	Yen *et al.* (1985)
Si-zu-wan	8 ~ 9	Lee *et al.* (1994)
Mud-volcanoes	7.87 ~ 9.18 (Wu-shan-ting) 8.26 ~ 8.30 (Gun-sheui-ping)	Lin (1997)
Si-zu-wan	8.24 ~ 8.44	Tsai (1984b)

cation: $Na^{+} > Ca^{+2} > Mg^{+2} > Al^{+3} > K^{+} > Fe^{+3}$

anion: $Cl^{-} > SO_4^{-2}$

4.3 Swelling, Slaking, and Permeability of Mudstone

The basic reason why the geological hazards frequently occurred in mudstone slopeland is that the mudstone creates swelling and slaking during a rain fall.

In Table 8, the study of Tsai (1984) showed that the main mineral composition in mudstone are quartz, illite, and chlorite, all of them do not have high potential to swell. Meanwhile, some cementation materials such as calcium aluminate hydrate ($CaO \cdot Al_2O_3 \cdot 10H_2O$; CAH_{10}) and calcium silicate hydrate (1.5 $CaO \cdot SiO_2 \cdot XH_2O$; CSH) are also contained in the mudstone.

Therefore, why the mudstone creates swelling and slaking phenomenon when it touches to water? Obviously, the swelling of the clay minerals in mudstone is not the main reason. The true reason could be the dissolve of the diagenesis bonds formed by CAH_{10} and CSH and the heavily deformed particles of mudstone, which compressed and consolidated by the overburden pressure during the process of sedimentation, rebound back to their original shape.

Once the mudstones at the surface absorb water, they rebound, swell, and then apart from the surface. In the second moment, the water would immediately permeate to the underlying layer of mudstone. Although the water-absorbed mudstones separate from the surface of fresh mudstone very slowly at the initial state, it gradually becomes quickly and seriously and eventually aparts from the surface of mudstone like a shower of blossom, and then, mudstone slakes.

An intact mudstone was taken from the site of Chong-ter Reservoir in Tien-Liao, Kaohsiung and was used to perform a series of swelling and slaking tests (Lee *et al*. 2002). Free swelling test and restricted swelling test were carried out on the mudstone specimens with diameter 5 cm and 2 cm in thickness. During the free swelling test, normal stress did not load on the specimen, but in restricted swelling test different normal stresses were needed. The results of free swelling tests are listed in Table 10, and shows that the swelling strain of the mudstone specimen under free swelling condition is rough 10.55% ~ 16.95%, average value is 12.45%. And from the record of test No. 4 shown in Fig. 5, the elapsed time for complete swelling approximates 10,000 minutes.

On the other hand, using normal stresses of 0.5, 1, 2, and 4 kgf/cm^2 (1 kgf/cm^2 = 0.1 MPa) to perform the restricted swelling tests, the test results are presented in Table 11 and Fig. 6. It is obvious that the larger the normal stress, the smaller the swelling strain is. Noticeably, the swelling strain approaches to zero, when the normal stress is 4 kgf/cm^2.

Plotting the data points of normal stress versus maximum swelling strain in Fig. 7, and the intersect of the relation line on the axis of abscissa showing the swelling pressure (with no swelling strain) of mudstone is about 4 kgf/cm^2(≒ 0.4 MPa).

Simultaneously, a series of slaking durability tests on the Tien-liao mudstone was carried out following the testing method suggested by ISRM (Lee *et al*. 2002). The results of the slake durability index for the first cycle (Id_1%) listed in Table 12 are distributing in the interval of 57.1% ~ 67.3%, the average is 62%. According to the classification standard proposed by Gamle (1971), the mudstone (Id_1% = 60% ~ 85%) is classified into the

Table 10　Free swelling test results of mudstone (Lee *et al.* 2002)

Test no.	Water content (before test) (%)	Water content (after test) (%)	Maximum swelling deformation (mm)	Maximum swelling strain (%)
1	8.02	16.45	2.21	11.05
2	4.39	16.16	3.39	16.95
3	8.05	16.89	2.25	11.25
4	8.61	20.60	2.11	10.55

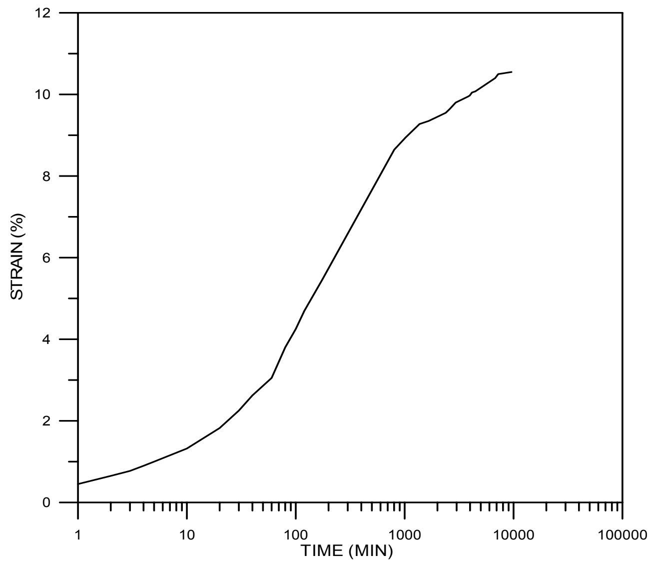

Fig. 5　The results of free swelling test (Test No. 4) (Lee *et al.* 2002)

Table 11　The results of restricted swelling tests (Lee *et al.* 2002)

Normal stress (kgf/cm^2)	Water content (before test) (%)	Water content (after test) (%)	Maximum swelling deformation (mm)	Maximum swelling strain (%)
0.5	4.56	9.59	0.51	2.55
1	5.73	11.63	0.33	1.65
2	5.63	10.12	0.22	1.10
4	4.34	8.91	0.03	0.15

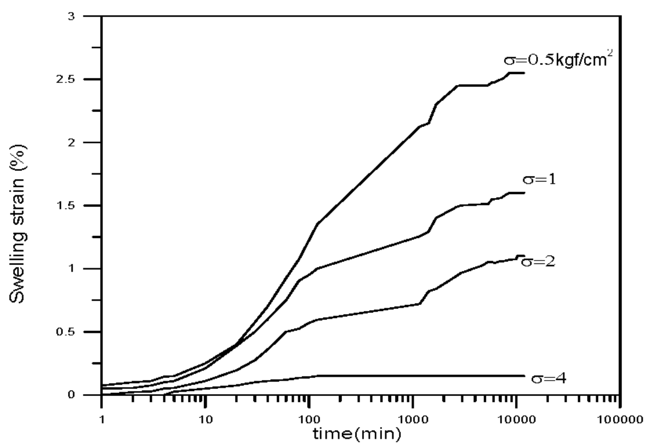

Fig. 6　The results of restricted swelling tests (Lee *et al.* 2002)

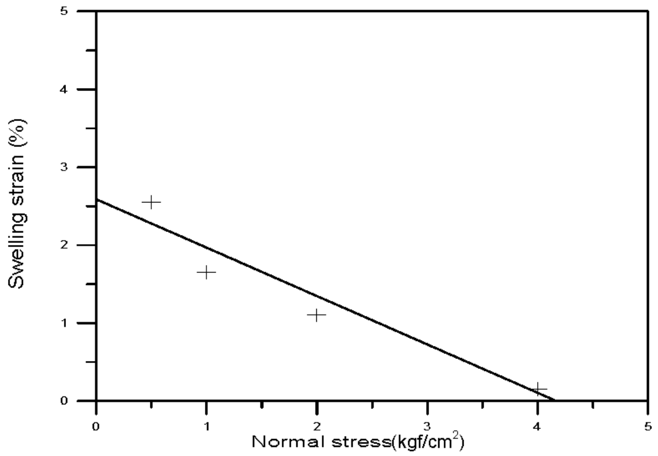

Fig. 7 The relation of maximum swelling strain vs. normal stress (Lee *et al.* 2002)

Table 12 The results of slaking durability tests for Chong-ter mudstione (Lee *et al.* 2002)

Sample No.	Sample description	Sample weight A (g)	Remain weight for 1st cycle B (g)	Remain weight for 2nd cycle C (g)	Slake durability index for 1st cycle Id_1 (%)	Slake durability index for 2nd cycle Id_2 (%)
No1	Gray mudstone	531.45	329.21	134.59	61.9	25.3
No2	Gray mudstone	491.34	330.76	159.86	67.3	32.5
No3	Gray mudstone	573.83	350.36	180.74	61.1	31.5
No4	Gray mudstone	584.09	378.31	245.9	64.8	42.1
No5	Gray mudstone	549.96	335.86	187.40	61.1	34.1
No6	Gray mudstone	576.41	329.21	134.59	57.1	23.3
No7	Gray mudstone	547.03	330.76	159.86	60.5	29.2

Notes: 1. Slaking durability test was performed by following the suggestion method of ISRM.
2. A、B、C are the dried sample weights; Id_1 = B/A, Id_2 = C/A.

Table 13 The permeability test results of mudstone (Juang 1976; Lee *et al.* 1984)

Tester	Testing method	Rock type	Sampling place	*K* (cm/sec)
Juang (1976)	Consolidation test	Intact mudstone	Yu-jin	$2.5 \times 10^{-7} \sim 1.0 \times 10^{-8}$
Lee (1984)	Constant-head permeability test	Intact mudstone	Si-zu-wan	$1.78 \times 10^{-8} \sim 3.14 \times 10^{-8}$

group of low durability. Similarly, the slake durability indexes for the second cycle (Id_2%) scatter in the range of 23.3% ~ 42.1%, the average is 31.1%, meaning that the mudstone is also distinguished as the class of low durability (Id_2% = 30% ~ 60%). Both of the Id_1% and Id_2% indicate that the mudstone do not have enough resistance to protect itself from the damage of slaking.

Juang (1976) and Lee *et al*. (1984) investigated the permeability of intact mudstone sampled from Yu-jin and Si-zu-wan, respectively. The coefficient of permeability (*k*) obtained by Juang (1976) from a consolidation test is $2.5 \times 10^{-7} \sim 1.0 \times 10^{-8}$ cm/sec. And, the $k = 1.78 \times 10^{-8} \sim 3.14 \times 10^{-8}$ cm/sec was got from a constant-head permeability test performed by Lee *et al.*

Liu (1912) carried out a series of one-dimensional consolidation test on mudflow material picked up from five mud-volcanoes and on intact mudstone from Gun-sheui-shan and Chen-chu-liao. The coefficients of permeability (*k*) for mudflow and intact mudstone were obtained as the $k = (0.1 - 5.3) \times 10^{-8}$ cm/sec for the intact mudstone of Gun-sheui-shan, and $k = (0.1 - 3) \times 10^{-8}$ cm/sec for the Chen-chu-liao mudstone. Thus, the permeability of mudstone material is extremely small.

4.4 The Strength of Mudstone

In this section, the mechanical behaviors of mudstone display under different loading conditions, such as uniaxial compression, triaxial compression, and shearing will be discussed. The results obtained from a new shearing test, ring shear test, will be also involved to compare with those of direct shear test.

(a) Uniaxial compression test of mudstone

Commonly, the natural water content of a mudstone core, which is being drilled up from the site, is about 20%. However, let the core be exposed to the air without covering any protecting sheet, the water content will decrease gradually, even down to near zero.

Some intact mudstone cores taken from Chai-shan, Kaohsiung were put into a testing specimen preparation box with temperature and moisture control. And then, ten mudstone specimens with different water content, distributing from 19.7% to 0.1%, were obtained for the testing of uniaxial compression.

The results of uniaxial compression tests are listed up in Table 14, and the influence of water content on the uniaxial compression strength of mudstone are plotted in Fig. 8 (Lee *et al*. 2003).

When the water content in mudstone specimen decreased from its natural state in the site, the uniaxial compression strength will increase obviously. For example, the uniaxal compression strength is 10.16 MPa for the specimen (No. U-E2) with water content *w* = 0.1%. The strength is about 2.5 times of the specimen (No. U-D2) with *w* = 5% and is also about 7.6 times of the one (No. U-A1) with *w* = 19.7%. Table 14 also shows that the dryer the specimen was, the smaller the axial strain at peak strength would be.

Conversely, the mudstone specimen with low water content produced large elastic modulus.

Accordingly, a mudstone will become stiffer and stronger, which is called "like a stone" when the rock is dried from its natural water content. On the contrary, it will change into "mud", while the water content increases much higher than the situation in original mudstone formation. Hence, water content is a governing factor when the strength and mechanical behaviors of mudstone are discussed.

(b) Triaxial compression test of mudstone

A series of triaxial compression test was conducted on the mudstone taken from Tien-liao, Kaohsiung (Lee 2007). The specimen was bored from mudstone block by air-drill method to prevent the mudstone core from absorbing water.

Table 14 The uniaxial compression test results of mudstone (Lee 2007)

Sample No.	Water content (%)	Peak strength (MPa)	Axial strain at peak strength (%)	Secant modulus (MPa)	Tangential modulus (MPa)
U-A1	19.7	1.34	6.3	20.3	26.0
U-A2	18.3	1.16	5.1	20.7	27.7
U-B1	13.5	1.94	4.5	42.1	44.8
U-B2	13.2	1.98	4.0	46.5	520
U-C1	10.8	2.40	2.3	127.9	107.0
U-C2	10.6	2.49	2.7	100.8	104.4
U-D1	5.0	3.72	1.7	209.8	246.0
U-D2	5.0	4.03	1.7	227.3	268.5
U-E1	0.3	7.50	1.8	496.9	528.0
U-E2	0.1	10.16	2.1	469.4	716.0

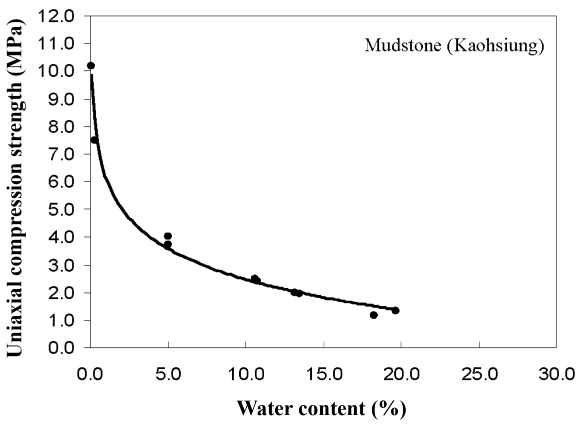

Fig. 8 The influence of water content on the uniaxial compression strength of mudstone

Air-dried specimens were used to carry out the tests by strain control with a rate of 0.2 mm/min in axial deformation. The confining pressures 10, 20, 40, 80, and 100 MPa were adopted to simulate the different initial stress states which mudstone had been subjected. The relation curves of deviatoric stress ($\sigma_1 - \sigma_3$) and axial strain for mudstone specimens, sample number ST-10, ST-20, ST-40, ST-80, and ST-100, are shown in Fig. 9. The confining pressure σ_3, the peak value of axial stress σ_{1p}, and the residual value of axial stress σ_{1r} for all of the specimens are presented in Table 15 with the initial size and air-dried weight of each specimen.

Figure 9 indicates that the air-dried mudstone specimen under a confining pressure smaller than 40 MPa will fail as a brittle material, *i.e.,* the deviatoric stress will fall down to a lower level after the peak strength. However, in the cases of confining pressure exceed 40 MPa, the deviatoric stress of the mudstone specimen will increase with the axial strain grows. No peak strength can be observed in the ($\sigma_1 - \sigma_3$)-ε_a curve, and the mudstone specimen behaves to be a ductile material. Therefore, the brittle- to-ductile transition pressure of the mudstone is defined as about 40 MPa.

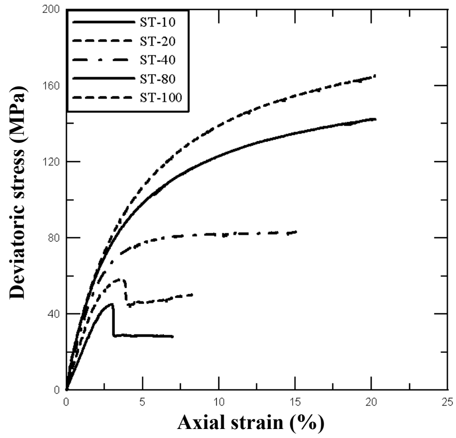

Fig. 9 The deviatoric stress-axial strain curves of air-dried mudstone specimen in triaxial compression tests

Table 15 The results of triaxial compression tests (Kaohsiung mudstone)

NO.	*D* (cm)	*H* (cm)	*W* (g)	γ_{ad} (kN/m^3)	σ_3 (MPa)	σ_{1p} (MPa)	Failure strain (%)	σ_{1r} (MPa)
ST-10	5.51	11.39	621.67	22.3	10	55	2.97	38
ST-20	5.51	11.17	609.71	22.5	20	78	3.59	67
ST-40	5.50	11.34	615.77	22.5	40	122	10*	122
ST-80	5.50	11.47	622.12	22.4	80	203	10*	203
ST-100	5.50	11.10	601.19	22.5	100	239	10*	239

Notice: * for the ductile failure, the peak strength is defined by the axial stress with 10% of axial strain.

Figures 10 and 11 show the plotting of Mohr's circles for the peak and residual strengths of each specimen on the τ (shear stress) – σ (normal stress) plane, respectively. And then, the peak and residual strength parameters of the mudstone, C_p = 13.16 MPa, φ_p = 20.02° and C_r = 3.14 MPa, φ_r = 28.21°, can be obtained from the Mohr's circle envelope of the two figures.

On the other hand, Lin (2000) picked up mudstone cores from Chai-shan, Kaohsiung, and then, changed the water content of the cores from natural state down to 14%, 10%, 5%, and 0.3%. These cores with different water contents were used to carry out a series of compression test and got the strength parameters for peak and residual strengths presented in Table 16. The test results show that both of the φ_p and φ_r increase with the decreasing water content. C_p also has the same inclination, but the moisture of specimen insignificantly influences on C_r.

(c) Direct shear test of mudstone

In the study, on the safety of a slope against sliding or failure, the shear strength of slope material obtained from direct shear test is commonly adopted. Chen (1997) used the mudstone cores taken from Chai-shan, Kaohsiung to conduct a series of direct shear tests. The mudstone specimens were treated to have different water contents before shear test. Four groups of specimen with w = 0 ~ 1%, 4 ~ 5%, 10 ~ 11%, 14 ~ 15% were prepared.

The direct shear tests with normal stress 2, 4, and 8 kgf/cm^2 (1 kgf/cm^2 = 0.1 MPa) were performed on each group of mudstone specimen. The testing results of τ (shear stress) – shear displacement for the group with w = 14 ~ 15% are shown in Fig. 12.

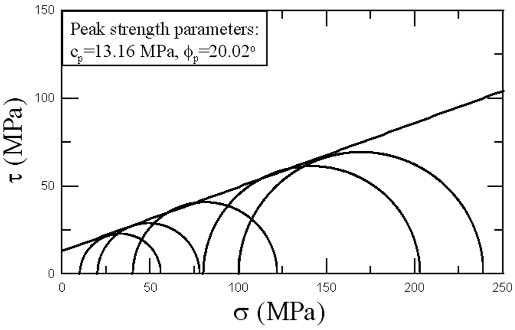

Fig. 10 Mohr-Coulomb's failure criterion for peak strength (Lee 2007)

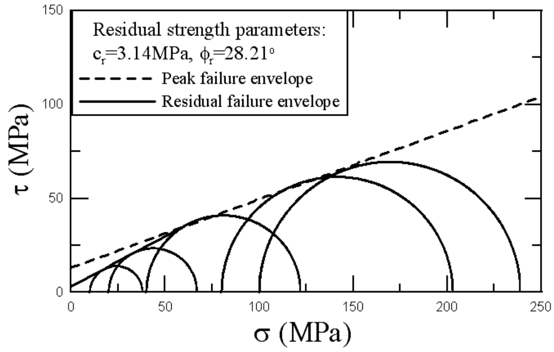

Fig. 11 Mohr-Coulomb's failure criterion for residual strength (Lee 2007)

Table 16 The triaxial compression strength parameters of intact mudstone under different water contents (Lin 2000)

Water content (%)	Peak strength		Residual strength	
	c_p (MPa)	φ_p (degree)	c_r (MPa)	φ_r (degree)
14%	0.72	15.1	0.34	18.7
10%	1.52	21.1	0.31	26.7
5%	1.53	26.7	0.39	29.3
0.3%	2.00	35.5	0.81	39.1

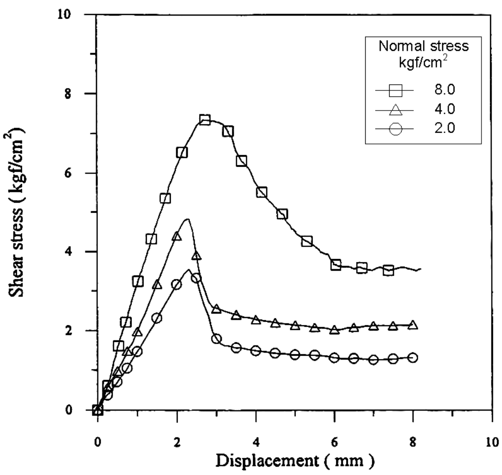

Fig. 12 The shear stress-shear displacement curves of intact mudstone (w = 14 ~ 15%) (Chen 1997)

All of the three curves of τ-shear displacement have peak strength and residual strength. But if we pay attention to the final part of these curves, all of them are not horizontal, this means that each mudstone specimen apparently reached the residual state, they do not yet touch to the "true" residual strength, even though the shear displacement already exceeded 8 mm.

Table 17 presents the peak strength parameters, c and φ, for the four groups of mudstone specimen with various moistures. Both of c and φ are increasing when the water content of mudstone specimen reduced.

(d) Ring-shear test of mudstone

The direct shear instrument is the most popular equipment to gain the shear strength of geological material but has an inherent defect in the shear box. Since the shear box is made up by two parts, upper box and lower box, the testing specimen in shear box will be sheared into two pieces when a failure plane formed in the middle of the specimen during shear test. If shear test continues, the contact area between the two pieces of specimen will decrease with the shear displacement increasing. Therefore, to dismiss the impact from the change of contact area, a larger shear displacement is not allowable in direct shear test; hence, the true residual strength can not be obtained.

To improve the shortcomings of direct shear instrument, the ring-shear instrument was developed. The ring-shear can keep the contact area of specimen constant during shear test and release the limitation on the shear displacement taken in direct shear test.

Liao (2004) used a ring shear equipment, shown in Fig. 13, to perform a comparison test with direct shear test on the mudstone specimen with existing failure plane. The purpose of using failed mudstone specimen for testing is to put the main attention on the shearing behavior after peak strength, especially to investigate the "true" residual state of each specimen.

Table 17 The shear strength parameters of mudstone (Chen 1997)

Sample No.	Water content (%)	Peak strength parameters	
		c (kgf/cm^2)	φ (°)
S-A	14-15	2.30	32.3
S-B	10-11	3.38	38.5
S-C	4-5	4.84	40.4
S-D	0-1	6.52	41.0

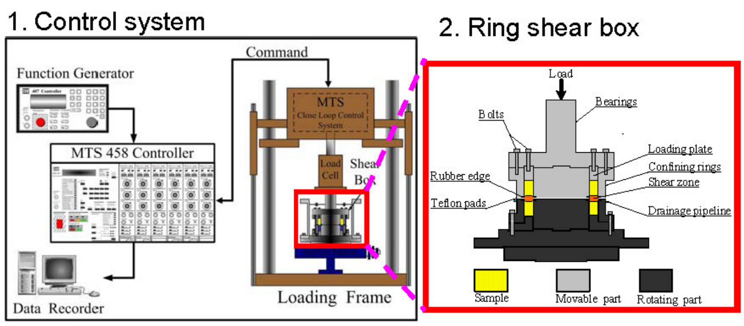

Fig. 13 The schematic feature of the ring shear instrument (Liao 2004)

Liao prepared two groups of air-dried mudstone specimens, one for direct shear test with 5 cm in diameter and 3.4 cm in height, but an artificial plane was set in the middle of specimens. The other group was for ring-shear test, each specimen was consisted of upper ring and lower ring and each ring had a height of 3.75 cm and its outer and inner diameters were 14.8 cm and 11.2 cm, respectively.

Both of the direct shear test and ring-shear test were carried out with the shear rate of 1.5 mm/min, and the normal stresses of 0.1, 0.2, and 0.4 MPa. The relation curves of shear stress (τ) against shear displacement (D) for direct shear tests is shown in Fig. 14. Similarly, Fig. 15 indicates the results from ring-shear tests.

Figure 14 shows that after the peak strength, the shear resistance of the three specimens continuously decreased even the shear displacement was more than 8 mm, about 16% of the specimen diameter. The specimen did not reach yet to a stable state with constant and minimum resistance for shear.

On the contrary, as shown in Fig. 15, the shear resistance of mudstone specimen can be measured till the shear displacement is more than 300 mm, and the shear resistance after the peak strength almost keeps a constant value, meaning that the stable state of shear resistance can be obtained, and it is the "true" residual strength of the specimen.

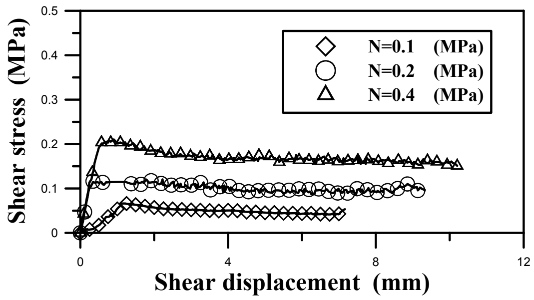

Fig. 14 The shear stress-shear displacement curves of the air-dried Ku-ting-keng mudstone under direct shear test (Liao 2004)

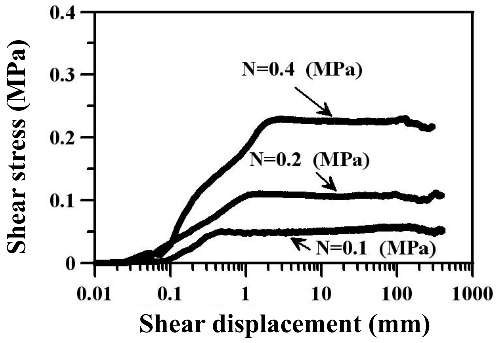

Fig. 15 The ring-shear test results of air-dried Ku-ting-keng mudstone (Liao 2004)

5. THE CHARACTERS OF MUDSTONE SLOPE

In this section, the symbol of the badland topographical feature – no vegetation covered on the slope, namely, bared slope, will be discussed about its distribution in the mudstone area. Then, the characteristics of bared mudstone slope, such as slope inclination, slope height, slope gradient, and erosion rate *etc.*, will also be investigated.

5.1 The Distribution of the Bared Mudstone Slope

In 1967, the former Bureau of Mountain Agriculture and Pasturage of Taiwan Government presented a report about the conservation and utilization situation in the southwestern mudstone area (Bureau 1967). The report pointed out that the bared zone in the investigation area was 2,532.58 hectares, and vegetation zone was 69,447.0 hectares. This investigation result means that in 1967, roughly 3.52% of the mudstone area was not covered with any vegetation. In the year of 1988, the Aerial Survey Office, Forestry Bureau published an investigation report on the bared zone in the southwestern mudstone area using Aerophotographs (Aerial Survey Office 1988). The investigation area was located across Tainan and Kaohsiung counties, the total area under investigation was 73,612.57 hectares, and the area without being covered with any vegetation was 3,826.28 hectares about 5.21% of the total investigation area. The investigation result shows that during the period of 1967-1988 the percentage of bared zone increased roughly 1.4%. In 1997, the Information System Research Center of Feng Chia University accepted a financial support from the Bureau of Water and Soil Conservation to perform a study on the distribution of bared zone in mudstone area by the satellite photographs (Bureau 1997). According to their report, the bared zone in southwestern mudstone area was increasing up to 11,179.5 hectares, much more than the record obtained in 1988. In 2005, the Fourth Engineering Office of the Bureau of Water and Soil conservation entrusted the Foundation of Slopeland Environment to investigate the distribution of mudstone formation in the area from Chiayi to Pintong. The photographs taken by the SPOT satellite were used to judge the amount of bared slopeland in every county of the investigation area (Fourth Engineering Office 2005). The report revealed that from 1998 till 2004, only a few increasing of bared zones created in Tainan county. And in 2004, the village had bared slopeland more than 100 hectares were: Zou-jeng (1,706.91 hectares), Nanhua (1,095.27 hectares), Ta-nei (436.54 hectares), and Long-chi (339.45 hectares). The most increment of bared slopeland was found at Long-chi, from 2001-2004, 66.56 hectares of new bared zone were created.

5.2 The Characteristics of the Bared Mudstone Slope

The topographical feature, slope direction, slope gradient, slope height, erosion rate, and slope surface temperature of a bared mudstone slope are quite different from those of a mudstone slope covered by vegetation. The difference in the characteristics of the slopes are discussed as follows:

(a) Slope direction and surface temperature of bared mudstone slope

The former Bureau of Mountain Agriculture and Pasturage of Taiwan Government (Bureau 1967) investigated the directions of bared mudstone slopes in southwestern mudstone area, and the investigation results are listed in Table 18. Besides the bared slopes formed from the river banks eroded by streams, most bared mudstone slopes concentrate on two groups, one is the multiple direction group, means a bared slope consists of several small slopes with different directions, the other is the southward direction group. The southward direction group contains three subgroups of slope with southward direction (17.8%), southeastward direction (13.14%) and southwestward direction (8.59%). Similarly, the report in 1988 (Aerial Survey Office 1988) also pointed out that except the bared mudstone slope along the riversides, the most popular directions of bared slope were the multiple directions and southward direction (involves the slope direction of south, southeast and southwest).

Chen (1984) also used aero-photos to inquiry the directions of bared slopes in southwestern mudstone area. The authors selected 208 bared mudstone slopes, and then, were classified into 16 groups according to the slope direction. The rose-chart of the bared slope direction is presented in Fig. 16 and shows that the group of northward direction is the least, but southward direction group is the most. And the groups of southeastward and southwestward directions also have a higher percentage about 10% ~ 15%.

Tien *et al.* (1989) investigated the relation between the amount of sunlight on the slope surface and the slope directions for the slopes located at the north latitude 23° in southwestern Taiwan. The slopes have the same slope angle 45° but with different slope directions from 0° ~ 360°. The amount of sunlight projected on unit area of each slope in spring, summer, and winter were calculated and plotted in Fig. 17. Only in the short period before and after the summer solstice, the sunlight projecting on the northward slopes is slightly more than that on the southward slopes. All the other days, the southward slopes receive most sunlight. Especially in the winter, the dry season of the southwestern mudstone area, the sunlight has the most significant projection difference from the southward and northward slopes. The southward slopes receive a lot of sunlight in a dry season, hence, the water content at the shallow depth in the southward direction mudstone slope will decrease even down to near zero. In such environment, the vegetation can not survive. Therefore, a high percentage of the mudstone slopes in southward direction is not covered with vegetation.

Hsu (1986, 1987) measured the surface temperature of mudstone slopes in southwestern mudstone area from January, 1986 to April, 1987, and four times of measurement were carried out. The maximum and minimum temperature and the temperature difference at the investigation period in the sites were recorded with different slope directions as listed in Table 19.

The investigation results showed that in sunny days (February 6 - 8, 1987), the highest maximum surface temperature (50.3°C) and the largest temperature difference (37.4°C) were measured from the southward mudstone slopes. And, the northward slopes had a lowest maximum surface temperature and a

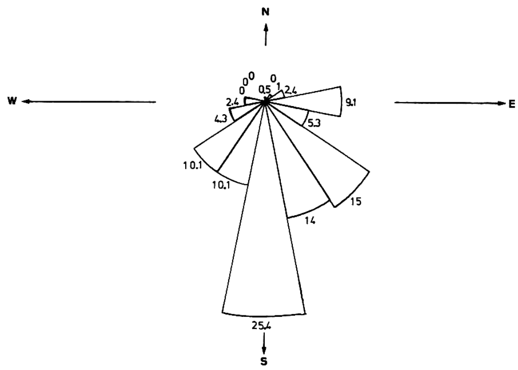

Fig. 16 The distribution of slope direction of bared mudstone slope (using aero-photos, sample number = 208) (Chen 1984)

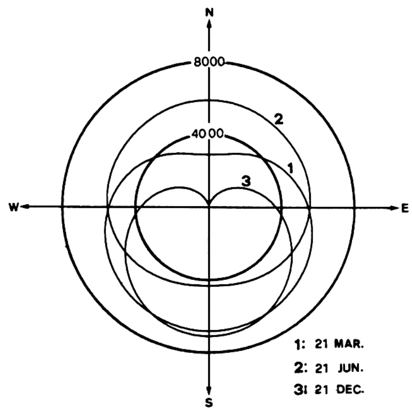

Fig. 17 The relation of the slope direction and the amount of sunlight for the mudstone slopes in southwestern Taiwan (north latitude 23°, slope angle 45°) unit: W · h/m^2 (Tien *et al.* 1989)

Table 18 The slope direction of bared mudstone slope (Bureau 1967)

Direction of bared slope	E	W	S	N	SE	SW	NE	NW	Multi-direction	Total
Area (hectares)	226.55	195.29	450.85	177.83	332.81	217.67	117.46	103.92	709.20	2532.58
Percentage	8.95%	7.71%	17.80%	7.02%	13.14%	8.59%	4.64%	4.10%	28.01%	100%

Table 19 The maximum and minimum surface temperature of mudstone slopes with different slope directions (Hsu 1986, 1987)

Test date	January 29-31, 1986 (cloudy)				April 3-5, 1986 (cloudy)				February 6-8, 1987 (fine)				April 2-4, 1987 (cloudy)			
Slope direction	E	S	W	N	E	S	W	N	E	S	W	N	E	S	W	N
Maximum temperature (°C)	31.3	37.5	37.5	24.4	37.5	40.3	37.8	31.0	39.5	50.3	43.3	25.8	46.4	46.0	41.7	29.3
Minimum temperature (°C)	13.7	14.5	14.3	13.5	20.3	20.5	20.8	20.9	10.2	12.9	11.7	9.9	20.3	19.3	19.7	19.3
Difference (°C)	17.6	23.0	23.2	10.9	17.2	19.8	17.0	10.1	29.3	37.4	31.6	15.9	26.1	26.7	22.0	10.0

smallest difference of temperature. The similar phenomenon can also be found in the data of cloudy weather (April 2-4, 1987). Moreover, the difference between the maximum surface temperature of southward and northward slopes was about 25°C and implies again that the surface temperature difference induced by the slope direction might be a vital factor that obviously impact on the growth of vegetation in slope. It may be also a reason that why the bared mudstone slopes are often found at the south side of a mudstone hill.

Furthermore, the surface temperature distribution of a mudstone slope can be observed carefully by a picture of thermalgraphy (Photo. 3) with the Photo. 4, which is the picture of the same bared mudstone slope at the "Moon World" in Tien-liao. The Photos 3 and 4 clearly indicate that the surface temperatures of the mudstone slopes with different directions at different parts distributed from 30°C to 50°C, and the temperature difference between vegetation and bared mudstone is more than 20°C.

(b) The gradient and height of bared mudstone slope

The investigation report presented by the former Bureau of Mountain Agriculture and Pasturage in 1967 (Bureau 1967) also collected the data of the relation of slope angle and bared area of the bared mudstone slope. As shown in Table 20, the slope angle was divided into seven categories as 30° ~ 35°, 35°~ 40°, 40° ~ 45°, 45° ~ 50°, 50° ~ 55°, 55° ~ 60°, and more than 60°. The sequence of the top four groups involving bared areas was (1) 40° ~ 45° (40.23%), (2) 45° ~ 50° (25.60%), (3) 35° ~ 40° (15.72%), (4) 50° ~ 55° (12.03%). This investigation result indicates that the mudstone slope with a slope angle of 40° ~ 45° has a highest potential to become a bared slope, and most of the bared slopes (93.58%) are in a slope angle in the range of 35° ~ 55°. On the contrary, only a few percent of bared slopes belongs to the steep slope (slope angle is 55° ~ 60°and more than 60°) and the moderate slope (slope angle 30° ~ 35°). All the slopes with a slope angle smaller than 30° (vertical: horizontal = 1:1.732) can prevent the slope from being bared.

Yen and Wu (1996) observed 70 developing bared slopes in the mudstone area and pointed out that 48 slopes (about 68.6%) had a slope height lower than 15 m, and only 10 slopes were higher than 20 m. Among the 70 slopes, 20 slopes continuously expended their bared zones, and the locations of the bared zones are concentrated on 6 - 12 m height.

Moreover, Fig. 18 indicates the investigation results that Chen (1994) compared the slope angle of the bared mudstone slopes in Kuang-miou formation with those in Nan-hua mudstone (Ku-tien-ken formation). Since the mudstone layer of Kuang-miou formation is lying between two thick layers of sandstone or siltstone, the mudstone slope can be protected by the sandstone as a cap rock. Contrarily, the Nan-hua mudstone was formed by a very thick layer of mudstone with some thin layers of sandstone, which could not provide enough protection as a cap rock can do. Therefore, the bared mudstone slopes with a cap rock (Kuang-miou formation) are always steeper than that in Nan-hua mudstone.

The effort of cap rock on the stability of mudstone slope was also observed by Lin (1995). In 1995, he investigated the development models of bared mudstone slope in Tien-liao "Moon World", and found out the influence of geological structure on the type of bared mudstone slope as:

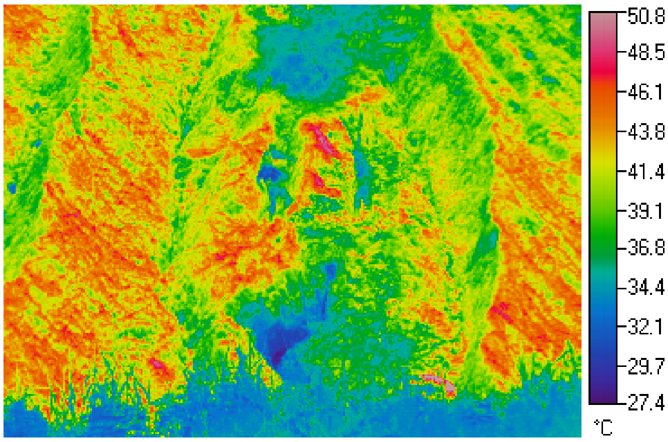

Photo 3 The surface temperature distribution of a bared mudstone slope in Tien-liao

Photo 4 The picture of the same bared mudstone slope in Tien-liao (shown in Photo 3)

Table 20 The slope angle and bared area of bared mudstone slope (Bureau 1967)

Slope angle	30°-35°	35°-40°	40°-45°	45°-50°	50°-55°	55°-60°	More than 60°	Total
Area (hectares)	18.66	398.00	1018.88	648.24	304.77	100.50	43.63	2532.58
Percentage	0.74%	15.72%	40.23%	25.60%	12.03%	3.97%	1.71%	100%

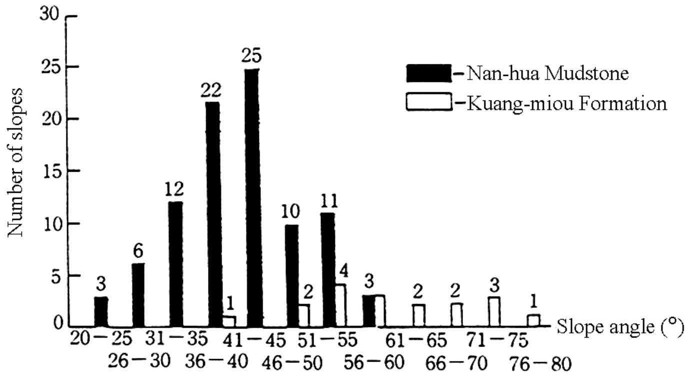

Fig. 18 The slope angle distribution of bared slope in Nan-hua mudstone and Kuang-miou formation (Lin 1995)

(1) The mudstone layer is covered by a horizontal layer (especially gravel layer), the bared slope is steeper and surface erosion can only put a slight impact on the slope development.

(2) The mudstone layer is massive without being covered by a horizontal layer on it , the lateral surface erosion is more obvious than the downward erosion and a wide and plain gully will be developed. The surface erosion will make the slope surface retreat parallelly.

(c) The erosion of mudstone slope

The former Bureau of Mountain Agricuture and Pasturage performed a site investigation on the conservation and reclamation of the failed mudstone slope in the Moon World of Tien-liao (Bureau 1974). They obtained a run-off coefficient on mudstone surface was about 0.83 ~ 0.87, average 0.85. In addition, they also measured the loss rate of surface soil during rain fall was 55.74 mm/1,000 mm (rainfall), and the erosion rate of mudstone slope was 6 ~ 8 cm/year.

Chen (1984, 1985, 1986) carried out a three years study on the slope erosion in Nan-hua mudstone area. After measuring a lot of erosion rates on bared mudstone slopes, an experimental equation about erosion rate of mudstone slope was achieved and some conclusions were also arrived as follows.

(1) The southward direction slope is easier to be eroded than the northward direction slope.

(2) The longer the slope is, the more serious the erosion will be.

(3) The steeper the slope is, the lower the erosion rate will be.

And, they also found out that the erosion thickness of many bared mudstone slopes during a rainy season is more than 10cm. Besides, Kuo and Lin (1988), measured the erosion thickness of a bared mudstone slope with slope angle 33° from March, 1997 to February, 1998, they got a average value of erosion thickness is 7.94cm. Chiu (1999) also investigated the erosion thickness of a natural bared mudstone slope with a moderate slope angle 35°, a erosion rate 10cm/year and the shape of gully, with a shallow trench at the top and gradually deeper to the bottom were observed.

Finally, the characters of mudstone slope mentioned in this section show that the mudstone slope with a slope angle 35° ~ 55° and slope height 6 ~ 12 meters has a higher risk to be a bared slope. If a cap rock on the top of a bared mudstone slope exists, the bared slope will be formed to a steeper one. Moreover, the erosion rate of a bared mudstone slope is influenced by slope direction, slope length and slope angle, and, the average erosion rate on a mudstone slope is about 10 cm/year.

6. THE GEOLOGICAL HAZARDS IN MUDSTONE SLOPELAND

Due to the weather condition in mudstone area is vividly divided into wet and dry seasons, as well as, mudstone possesses some special physical and chemical properties, the slopelands in mudstone area are easily to be eroded by rainfall and finally to be formed a landscape like in the Moon, *i.e.* a symbol of badland topography. Hence, the slope erosion is the most serious geological hazard in mudstone area.

In addition to the slope surface erosion and the mudflow induced by slope erosion, sliding of weathered layer and rock falling are the common geological hazards happen in natural mudstone slope. In artificial mudstone slopes, including cut and fill slopes, surface erosion, slope failure, sliding of vegetation layer, as well as, mudflow, subsidence and piping usually create severe damages on the slopes.

Moreover, based on the analysis on 46 failed artificial mudstone slopes, involving highway slopes and the slopes of large scale excavation sites, the hazards commonly occur in mudstone slope can be understand in more detail (Lee *et al.* 1990).

The relation of the slope angle and the slope failure modes is presented in the Fig. 19. Twenty-one slopes (45.6% of all samples) failed with plane sliding, the rock falling happened in 18 slopes (39.1% of all slopes), however, only one slope failed by mudflow. In addition, three observation results are shown as follows:

(1) Most of the failed mudstone slopes have a slope angle larger than 30°.

(2) The plane sliding failure almost induced by the sliding of weathered layer or vegetation layer on the slope with a slope angle of 30° ~ 50°.

(3) 75% of the rock falling occurred in the bared mudstone slope with a slope angle steeper than 50°.

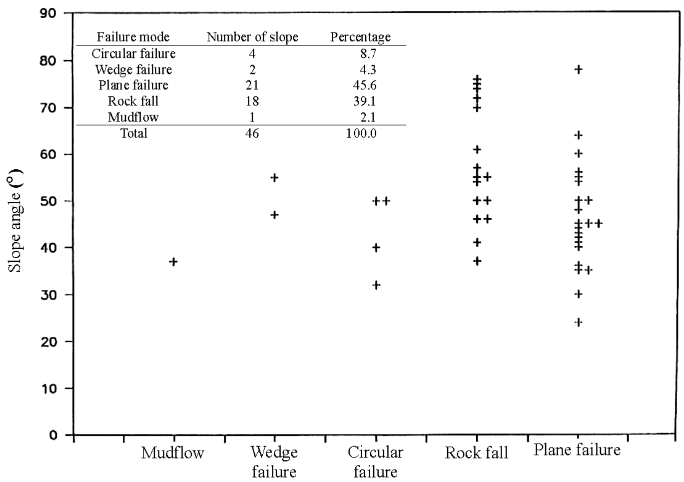

Fig. 19 The relation of slope angle and slope failure mode of mudstone slopes (Lee *et al.* 1990)

7. CONCLUSIONS

This paper overviewed the geological and weather conditions of the southwestern mudstone area and discussed the basic properties of mudstone material and mudstone slopes as well as the geological hazards in mudstone slopeland. Some remarkable conclusions are arrived and presented.

The global warming has strongly influenced on the weather condition of the southwestern mudstone area. The average yearly temperature in Tainan and Kaohsiung during 2001-2006 is higher than the average of the last thirty years of 20th century about 0.6°C. The average yearly rainfall also increased 51 mm for Tainan and 86 mm for Kaohsiung in the same period. The number of month, which has an average monthly rainfall over 400 mm, was only one (August) in the period of 1971-2000 but changed to two (June and July) at the period of the initial six years of 21th century. The impacts induced by global warming – temperature raising, rainfall concentration, rainfall intensity increasing, rainy days decreasing, and risk of drought up, are gradually revealed in the southwestern mudstone area. These impacts may lead more serious geological hazards in mudstone area than the past ages.

The mudstone in southwestern Taiwan is a geological material with low plasticity (average 14 ~ 18%), low durability (Id_1 = 62.0%, Id_2 = 31.1%), low permeability ($k = (1.0 - 25) \times 10^{-8}$ cm/sec) and light alkaline (pH ≒ 8-9).

The swelling pressure produced by intact mudstone is about 0.4 MPa. The strengths of mudstone (under the uniaxial or triaxial compression) are remarkably influenced by the water content of the specimen itself.

The surface erosion problem is the most serious geological hazard in mudstone slopeland. The problem bares a slope and finally forms a badland topography like the famous geological spot Moon World in Tien-liao, Kaohsiung.

The slope surface erosion is apparently governed by the slope direction, slope length and slope angle. The mudstone slopes with a slope direction of south, south east and south west have a highest potential to be a bared slope, as well as the mudstone slope has a slope angle of 35° ~ 55° and slope height of 6 ~ 12 meters, it also easily to become a bared one. The average erosion thickness in mudstone slope is about 10 cm per year.

Most of the failed artificial mudstone slopes have a slope angle larger than 30°. The sliding of weathered layer or vegetation layer, as well as, rock falling are the most common failure modes of artificial mudstone slopes.

ACKNOWLEDGEMENTS

The authors deeply appreciate the long-term financial support from the National Science Council and the Council of Agriculture, Executive Yuan of Taiwan on investigating the disaster mitigation on mudstone slopes to have extensive research results referenced by this study.

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