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RESEARCH ARTICLE

SWELLING CLAY MINERALS AND SLOPE CUT FAILURES IN THE GARINONO FORMATION ALONG JALAN SUNGAI HITAM, LIBARAN, SANDAKAN

John Kuna Raj

Engineering Geology Consultant, No.83, Jln. Burhanuddin Helmi 2, Tmn. Tun Dr. Ismail, 60000 Kuala Lumpur, Malaysia.
****Corresponding Author Email: jkr.ttdi.tmc@gmail.com***

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ABSTRACT

Jalan Sungai Hitam in the Sandakan Peninsula traverses a flat to gently undulating terrain of low hills and ridges surrounded by broad alluvial flats. Recent slope cuts expose bluish to dark grey mudstones of the Garinono Formation containing pebble to boulder sized, angular to rounded, blocks of sandstone and other rock types. Slump-mud flows have occurred at most of the slope cuts; the failed materials characterized by desiccation cracks and fissures. Soil index properties, including consistency limits and grain size analyses, indicate that the mudstones have a medium to high swell potential. X-ray diffraction analyses show the clay minerals present to be kaolinite, illite and randomly interstratified illite-montmorillonite (a swelling clay mineral). The mudstones are thus sensitive to atmospheric wet-dry cycles with repeated swelling and shrinkage giving rise to the desiccation cracks and fissures, The cracks and fissures reduce the shear strength of the mudstones and allow for the infiltration of rainwater which initiates the slump-mud flows. It is concluded that earthworks in areas of the Garinono Formation in eastern Sabah need to consider the presence of swelling clay minerals; an occurrence that can be inferred from evaluating soil index properties.

KEYWORDS

swelling clay minerals, Garinono Formation, soil index tests.

1. INTRODUCTION

In north and west Sandakan Peninsula is found undulating to hummocky terrain developed over bedrock mapped as the Garinono Formation by the Geological Survey of Malaysia (Lee, 1970). This Formation was first named by Collenette for what was then interpreted as a tilloid deposit that out-cropped between Miles 22 and 35 of the Sandakan-Telupid Road (Labuk Road). The Formation was considered to be Neogene or younger in age and consisted largely of mudstone with blocks of other rock types of very variable size. The mudstone is mainly a stiff, bluish plastic clay, showing no indications of bedding or lineation, though more rarely it is grey or reddish grey and may contain shaly laminations (Collenette, 1966). Collenette (1966) stated that problems were likely to be encountered in earthworks involving the Garinono Formation as the Formation assumed a very low angle of rest. Cuts at the then Mile 31.75 of the Labuk Road for instance, were excavated with face angles of about 30^o, but after heavy rain in early 1965, developed slumps at several places; the failed material flowing half-way across the road and assuming an almost horizontal angle of rest. Reasons for the low angle of repose were not discussed, though Collenette (1966) noted that the physical characteristics of the Garinono Formation were unusual and needed to be considered in any engineering project and resettlement scheme.

Jacobson et al. (1970) described the Garinono Formation as being a slump breccia with some steeply dipping soft mudstone, tuff and tuffite.

The slump breccia consisted of rock blocks of varying types, hardness and size in a stiff clay matrix. The blocks often formed hills with steep slopes, whilst the mudstone, tuff and tuffite formed low hills with gentle slopes. Rock blocks present included sandstone, limestone, basalt, gabbro, chert and ultrabasic rocks (Jacobson et al., 1970).

Jacobson reported that a site investigation in the Sungai Manila Settlement Scheme in the Sandakan Peninsula had classified the Garinono Formation there as a bouldery mudstone with sandstone blocks of variable size in a brown to grey, highly plastic clay matrix. The large boulders at shallow depths were considered likely to obstruct piling, whilst the clay type present indicated that there might be a great loss in strength for a comparatively small increase in moisture content. It was thus considered necessary that good drainage be provided and water prevented from reaching the footing (Jacobson et al., 1970).

Clennell (1992) describes the outcrop area of the Garinono Formation in eastern Sabah as comprising melange and broken formations (of Middle Miocene to Oligocene age) composed mainly of sandstone blocks in a shaly matrix together with a small volume of admixed igneous material, chert and limestone. Clennell (1992) introduced the term "Garinono Melange Unit" (GMU) which he subdivided into two main Members. The matrix of the Grey Member is bluish to dark grey in colour; its' clay minerals mainly illite-mica, chlorites and kaolinite and locally present smectite and interlayered illite-smectite. The matrix of the Red Member, however, is

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dominantly red in colour; the clay minerals being mainly smectite or interlayered illite-smectite with variable amounts of chlorite (Clennell, 1992).

Clennell (1992) noted that outcrops of the Garinono Formation were characterized by uneven topography and very unstable surface slopes due to the soft matrix, punctuated by scattered resistant blocks. Some of the matrix also contained swelling clays, which worsened stability problems during wet weather. Road cuts through the melanges therefore, had to be made at a very shallow angle, and this was said to increase the expense of highway projects (Clennell, 1992).

A site visit to the Sandakan Peninsula in February 2014 noted that slump-mud flows had occurred at several cuts exposing mudstones of the Garinono Formation along the then newly constructed Jalan Sungai Hitam in Libaran. The failed materials were characterized by the presence of desiccation cracks and fissures; features usually associated with swelling or expansive clays. This paper discusses identification of swelling clay minerals in the Garinono Formation from soil index properties as well as X-ray diffraction analyses. The paper also discusses the causes for the slump-mud flows that have occurred.

2. Study Area

Jalan Sungai Hitam in Libaran traverses a flat to gently undulating terrain of low hills and ridges separated by broad tracts of alluvial flats and swamps. Much of this terrain is now covered by oil palm plantations. The road starts at the roundabout at Kampung Sungai Tiram and extends south for some 1.6 km, before veering southwest and continuing for over 5 km to a settlement on the east bank of Sungai Tendok Besar (Figure 1).

A number of slope cuts are found along the road, especially towards the southwest where the road passes through a ridge that rises to some 50 m above sea-level. The slope cuts were excavated between 2012 and 2013, and at the time of the site visit in February 2014 were partly to completely covered by vegetation in the form of creepers, ferns, grass and shrubs. Details on the locations and other features of the individual cuts are provided in Table 1.

The cuts are benched and up to 9 m in height with overall cut angles of about 35º. The benches in many cases, however, cannot be differentiated as the cut faces are very irregular and hummocky due to repeated failures. The failures are best classified as slump-mud flows, for they start as slumps which degenerate into mud flows with lobate fronts. The failed materials themselves, have also sometimes moved downslope as mudflows. The failed materials and in some cases, the in situ slope materials, are characterized by the presence of desiccation cracks and fissures that are up to about 1 m deep.

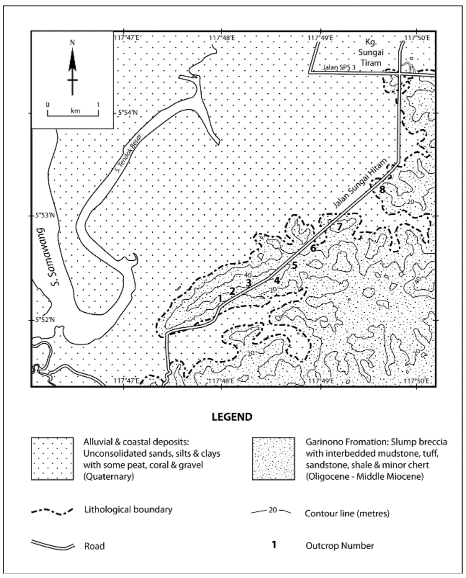

Figure 1: Geology map of the Kg. Sungai Tiram area, Libaran, Sandakan. [After Lee (1970) and field mapping]

It is to be noted that similar failures have been reported at cuts in expansive soils along the Xiangfan-Chongqing, and Chengdu-Kunming, railway lines in China (Xiao et al., 2017; 2018). These expansive soils are reported to be sensitive to atmospheric wet-dry cycles with repeated swelling and shrinkage giving rise to cracks and fissures. The cracks and fissures cause a sharp decrease in shear strength and allow for infiltration of rainwater which causes a sudden landslide. These failures were called "shallow surface slides" for they have depths of between 1 and 2.5 m; depths close to the depth of fissure development and atmospheric weathering (Xiao et al., 2017; 2018).

Table 1: Features of outcrops (slope cuts) along Jalan Sungai Hitam, Libaran, Sandakan

Outcrop (Slope cut)	Mid Point Coordinates	Description
1 (North side)	5º 52' 12.13"N 117º 48' 5.60'E (65 m length) (6 m height)	Irregular cut face with several slump-mud flows partly covered by vegetation. Dark grey mudstone with pebble to cobble sized, clasts. Desiccation cracks & fissures in slope and failed materials.
2 (North side)	5º 52' 14.19"N 117º 48' 9.08'E (100 m length) (6.5 m height)	Irregular cut face with several slump-mud flows partly covered by vegetation. Dark grey mudstone with pebble to boulder sized, clasts. Desiccation cracks & fissures in slope and failed materials.
3 (North side)	5º 52' 23.54"N 117º 48' 25.60'E (145 m length) (9 m height)	Irregular cut face with several slump-mud flows partly covered by vegetation. Dark greenish grey mudstone with cobble sized, clasts. One rounded spillite boulder (3.6 m size). Desiccation cracks & fissures in slope and failed materials.
4a (North side)	5º 52' 28.32"N 117º 48' 33.06'E (160 m length) (7 m height)	Irregular cut face with several slump-mud flows partly covered by vegetation. Dark grey mudstone with pebble to boulder sized, clasts. Gulleys & slaking of mudstone towards east end. Desiccation cracks & fissures in slope and failed materials. Recent flows of failed materials.
4b (South side)	5º 52' 28.32"N 117º 48' 33.06'E (100 m length) (7 m height)	Irregular cut face with several slump-mud flows partly covered by vegetation. Dark grey mudstone with pebble to boulder sized, clasts. Desiccation cracks & fissures in slope and failed materials.
5 (North side)	5º 52' 35.76"N 117º 48' 42.06'E (180 length) (8 m height)	Irregular cut face with several slump-mud flows partly covered by vegetation. Dark grey mudstone with pebble to boulder sized, clasts. Desiccation cracks & fissures in slope and failed materials.
6 (North side)	5º 52' 38.80"N 117º 48' 45.67'E (90 m length) (9 m height)	Irregular cut face with several slump-mud flows partly covered by vegetation. Dark grey mudstone with pebble to cobble sized, clasts. Desiccation cracks & fissures in slope and failed materials.
7 (South side)	5º 52' 45.30"N 117º 48' 53.09'E (15 m length) (4 m height)	Irregular cut face with a few slump-mud flow mostly covered by vegetation. Dark grey mudstone with pebble to cobble sized, clasts. Desiccation cracks in slope and failed materials.

8 (North side)	5° 52' 56.87"N 117° 49' 6.72'E (125 m length) (10 m height)	Irregular cut face with a few slump-mud flows partly covered by vegetation. Dark grey mudstone with pebble to boulder sized, clasts. Many gulleys and slaking of slope materials. Desiccation cracks in slope and failed materials.
8 (South side)	5° 52' 56.87"N 117° 49' 6.72'E (125 m length) (10 m height)	Irregular cut face with a few slump-mud flows partly covered by vegetation. Dark grey mudstone with pebble to boulder sized, clasts. Many gulleys and slaking of slope materials. Desiccation cracks in slope and failed materials.

3. Methodology

In view of the desiccation cracks and fissures, it was suspected that swelling or expansive clay minerals were present in the mudstones of the Garinono Formation along Jalan Sungai Hitam. Mudstone samples were thus collected from various slope cuts for identification of the clay minerals present through x-ray diffraction analyses. Several soil index properties of the mudstones were also determined as they can be used to infer the presence of swelling or expansive clay minerals (Sridharan and Prakash, 2016).

3.1 Grain Size Analysis

Grain size analysis refers to determination of the percentage of particles of different sizes present in a soil. The analysis essentially involves two main methods; the use of sieves for coarse grained (>0.075 mm size) particles, and sedimentation methods for finer grained particles. Grain size analyses are widely used in the classification of soils and have also been applied to classify the swell potential of soils. Chen (1965) for instance, proposed use of the clay (<0.0039 mm size) content to identify the swell potential, whilst Holtz and Gibbs (1956) proposed use of the colloid (<0.001 mm size) content. As the mudstones in the present study consist predominantly of silt and clay sized particles, the sedimentation method was employed to determine their grain size distribution. The procedure for carrying out these determinations followed that described in ASTM D 422-54 T (1958).

3.2 Plastic and Liquid Limits

Consistency refers to the strength and resistance to penetration of a soil under in situ conditions and is largely governed by the water content (Wagner, 2013). As water is added to a fine-grained soil, the consistency changes from solid to semi-solid to plastic, and finally to liquid. Consistency limits are used for the classification of soils and have also been applied to identify the swell potential of soils. Chen (1965), Snethan et al., (1977) and IS 1498 (1970) have used the liquid limit to classify the swell potential of soils, whilst Holtz and Gibbs (1956), Chen (1988) and IS 1498 (1970) have used the plasticity index. Sridharan and Prakash (2016) have also noted that "soil activity" has been used to identify the swell potential of soils, the "soil activity" is the ratio of the plasticity index to the fine-grained clay (<0.002 mm) percentage content. In this study, determination of the liquid and plastic limits of the fine-grained fractions (i.e. <0.425 mm in size) of the sampled mudstones was carried out according to the procedures described in the Handbook of the Road Research Laboratory (RRL, 1952).

3.3 Linear Shrinkage

Linear shrinkage refers to the percentage decrease in length of a soil sample when it is oven-dried after starting at a moisture content at about its liquid limit. Based on the value of the percentage linear shrinkage (LS), soils can be classified as having low (0-12%), medium (12-17%), high (17-22%) or very high (>22%) shrinkage (SAA, 1977). Determination of the linear shrinkage of the fine grained fractions (i.e. <0.425 mm in size) of the sampled mudstones was carried out according to the procedure described in the Methods of Testing Soils for Engineering Purposes by the New South Wales Department of Sustainable Natural Resources (SAA, 1977).

3.4 X-ray diffraction analysis

Clay fractions for the x-ray diffraction analyses were first prepared according to the decantation procedure described in the USGS Laboratory Manual for X-ray Diffraction (Poppe et al., 2001). Sodium Hexametaphosphate (Calgon) was used as the dispersing agent, whilst glass slides were employed for preparation of oriented aggregate mounts as described in the same Manual. The oriented aggregate mounts were scanned with an Empyrean fully automated multi-purpose x-ray diffraction instrument manufactured by Malvern Panalytical. The scans were carried out using Cu Kα radiation with generator settings at 40 kV and 40 mA. The scans were all performed using a continuous scan mode from 2° to 40° 2θ at 2° per minute with a step size of 0.026° 2θ.

The aggregate mounts were all scanned under four different conditions:

1. normal or untreated scan,
2. scan after ethylene glycol vapor treatment (method of Poppe et al., 2001),
3. scan after heating to 350°C for one hour, and
4. scan after heating to 550°C for one hour.

No problems of peeling or cracking of the oriented aggregate mounts were encountered during the various treatments.

4. Results

4.1 Grain Size Analysis

Results of the sedimentation analyses show the mudstones to have large contents of clay and silt sized particles (Table 2). Silt sized particles form some 24% to 35% of the sampled mudstones, whilst the clay fraction (<0.0039 mm) is about 35% to 47%. These results are comparable with those of Baba Musta et al. (2017) who report clay contents of 34.6% to 41.6%, silt contents of 33.6% to 49.8%, and sand contents of 15.3% to 29.5% for five samples of weathered melange from Sandakan. In the sampled mudstones furthermore, fine grained clays (<0.002 mm size) form some 28% to 40%, whilst the colloids (<0.001 mm size) are about 20% to 28% (Table 2). On the basis of the percentage content of fine-grained particles, Table 3 shows that the sampled mudstones all have a medium swell potential in the classification scheme of Chen (1965), but a high swell potential in the scheme of Holtz and Gibbs (1956).

Table 2: Percentage content of fine-grained particles in mudstones from different outcrops (slope cuts) along Jalan Sungai Hitam, Libaran, Sandakan.

Outcrop	Sample Number	Silt (0.0039-0.063 mm)	Clay (<0.0039 mm)	Fine Clay (<0.002 mm)	Colloids (<0.001 mm)
1	01 S1	24%	36%	30%	22%
1	01 S2a	25%	40%	33%	20%
2	02 S2	28%	47%	40%	28%
4	04S1	35%	45%	31%	26%
6	3a1	30%	35%	28%	23%
8	5a	30%	42%	33%	27%
8	08 S1	38%	47%	33%	23%

Table 3: Swell potential classification of mudstones based on percentage content of fine-grained particles (Class limits after Chen, 1965; Holtz and Gibbs, 1956)

Outcrop	Sample Number	Clay (<0.0039 mm)	Class (Chen, 1965)	Colloids (<0.001 mm)	Class (Holtz & Gibbs,1956)
1	01 S1	36%	Medium	22%	High
1	01 S2a	40%	Medium	20%	High
2	02 S2	47%	Medium	28%	High
4	04S1	45%	Medium	26%	High
6	3a1	35%	Medium	23%	High
8	5a	42%	Medium	27%	High
8	08 S1	47%	Medium	23%	High

4.2 Plastic and Liquid Limits

Fine grained fractions of the sampled mudstones show a fairly small variation in plastic, and liquid, limits as well as plasticity indices (Table 4). Plastic limits are between 22.0% and 25.4%, liquid limits between 40.8% and 45.2%, and plasticity indices between 16.4% and 20.1%. These results are comparable with those of Baba Musta et al. (2017) who report liquid limits of 45% to 60% and plasticity indices of 23% to 34% for five samples of weathered melange from Sandakan.

In terms of the liquid limit. Table 5 shows that the sampled mudstones all have a high swell potential in the scheme of Chen (1965), but a low swell potential in the scheme of of Snethan et al. (1977) and a medium swell potential in the scheme of IS 1498 (1970). In terms of the plasticity index, Table 6 shows that the mudstones all have a medium swell in the classification schemes proposed by Holtz and Gibbs (1956), Chen (1988) and IS 1498 (1970). In terms of the "activity index" of Sridharan and Prakash (2016), however, all the sampled mudstones would be classified as being "inactive"" (Table 7).

Table 4: Consistency limits of mudstones from different slope cuts along Jalan Sungai Hitam, Libaran, Sandakan

Outcrop	Sample Number	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index (%)	Linear Shrinkage (%)
1	01 S1	22.7	41.3	18.6	11.7
1	01 S2a	22.0	41.9	19.9	11.6 (Bowed)
2	02 S1	24.0	43.8	19.8	11.4
2	02 S2	24.2	42.1	17.9	11.1
3	03 S1	24.3	40.9	16.6	-
4	04 S1	24.7	44.5	19.8	-
6	3a1	25.1	45.2	20.1	6.6 (Bowed)
7	07 S1	25.4	41.8	16.4	-
8	5a	24.1	40.8	16.7	11.5 (Bowed)
8	08 S1	25.0	43.2	18.2	-

Table 5: Swell potential classification of mudstones based on liquid limit (Class limits after Chen, 1965; Snethan et al.; 1977; IS:1498, 1970)

Outcrop	Sample Number	Liquid Limit (%)	Class (Chen, 1965)	Class (Snethan et al., 1977)	Class (IS: 1498, 1970)
1	01 S1	41.3	High	Low	Medium
1	01 S2a	41.9	High	Low	Medium
2	02 S1	43.8	High	Low	Medium
2	02 S2	42.1	High	Low	Medium
3	03 S1	40.9	High	Low	Medium
4	04 S1	44.5	High	Low	Medium
6	3a1	45.2	High	Low	Medium
7	07 S1	41.8	High	Low	Medium
8	5a	40.8	High	Low	Medium
8	08 S1	43.2	High	Low	Medium

Table 6: Swell potential classification of mudstones based on plasticity index (Class limits after Holtz and Gibbs, 1956; Chen, 1988; IS:1498, 1970)

Outcrop	Sample Number	Plasticity Index(%)	Class (Holtz and Gibbs, 1956)	Class (Chen, 1988)	Class (IS: 1498, 1970)
1	01 S1	18.6	Medium	Medium	Medium
1	01 S2a	19.9	Medium	Medium	Medium
2	02 S1	19.8	Medium	Medium	Medium
2	02 S2	17.9	Medium	Medium	Medium
3	03 S1	16.6	Medium	Medium	Medium
4	04 S1	19.8	Medium	Medium	Medium
6	3a1	20.1	Medium	Medium	Medium
7	07 S1	16.4	Medium	Medium	Medium
8	5a	16.7	Medium	Medium	Medium
8	08 S1	18.2	Medium	Medium	Medium

Table 7: Activity classification of mudstones (Class limits after Sridharan and Prakash, 2016)

Outcrop	Sample Number	Fine Clay (<0.002 mm)	Plasticity Index	Activity	Classification
1	01 S1	30%	18.6%	0.62	Inactive
1	01 S2a	33%	19.9%	0.60	Inactive
2	02 S2	40%	17.9%	0.45	Inactive
4	04 S1	31%	19.8%	0.64	Inactive
6	3a1	28%	20.1%	0.72	Inactive
8	5a	33%	16.7%	0.51	Inactive
8	08 S1	33%	18.2%	0.55	Inactive

4.3 Linear Shrinkage

Results of the linear shrinkage tests indicate that five of the samples (i.e. with values of 11.1 to 11.7%) would be classified as having medium linear shrinkage, whilst the remaining one sample would have low linear shrinkage (Table 4). It is interesting to note that two of the six tested samples bowed (or arched) upward after oven-drying; a feature that is indicative of expansive soils (Cerato and Lutenegger, 2006). The results of the present tests are comparable with the linear shrinkage values of between 12.1% and 17.1% reported by Baba Musta et al. (2017) for five samples of weathered melange from the main road in Sandakan.

4.4 X-ray diffraction analysis

X-ray diffraction analyses were carried out on several oriented aggregate mounts of the clay fractions of the sampled mudstones, though the results of only three specimens are displayed as these involve duplicate determinations (Figures 2 to 7). Criteria for identification of the clay minerals is based on differences in the scans under the four conditions earlier described as shown in Table 8 (after Thorez, 1975; Poppe et al., 2001). The clay minerals illite, kaolinite and randomly interstratified illite montmorillonite are present in all the sampled mudstones, though their relative contents are somewhat variable (Table 9). Differences in the heights and areas of the peak reflections on the scans can be used to estimate the quantitative content of the clay minerals, though this has not been done in view of the broad diffraction bands present. The non-clay minerals quartz and goethite furthermore, are seen in the clay fractions of some sampled mudstones (Table 9); goethite only been seen in the 500°C heated scans. It is to be noted that x-ray diffraction analyses of five samples of weathered melange from Sandakan have shown the main minerals present to be quartz, kaolinite and illite (Baba Musta et al., 2017).

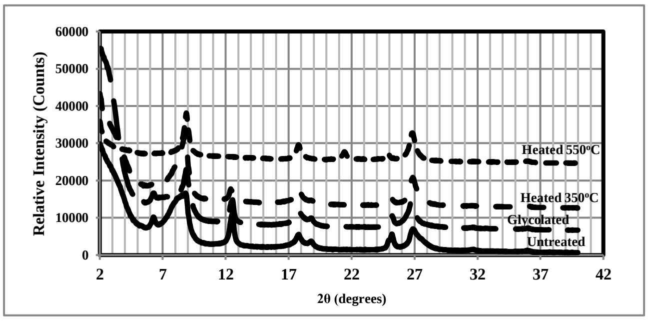

Figure 2: X-ray diffractograms of sample from Outcrop 1 (Scans R 4917)

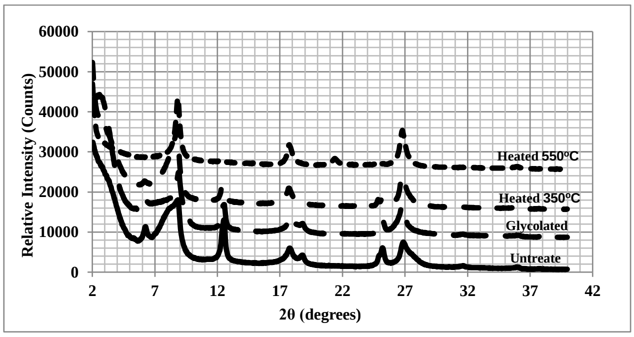

Figure 3: X-ray diffractograms of duplicate sample from Outcrop 1 (Scans R 4920)

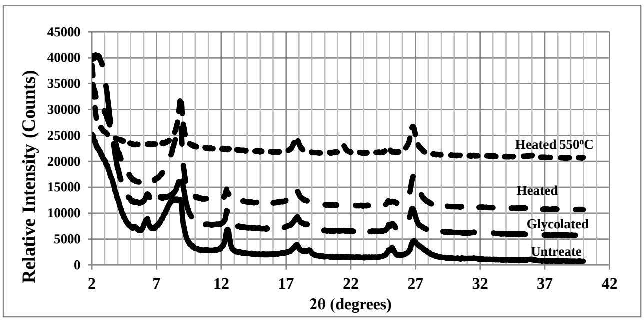

Figure 4: X-ray diffractograms of sample from Outcrop 6 (Scans R 4918)

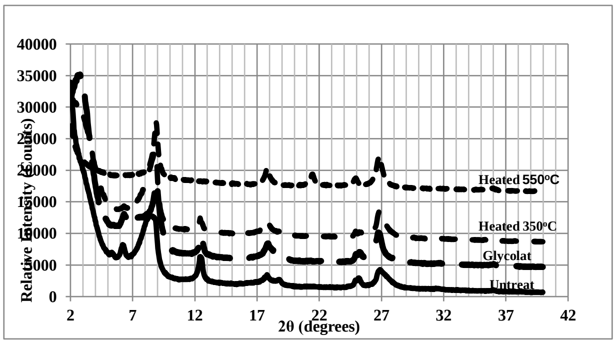

Figure 5: X-ray diffractograms of duplicate sample from Outcrop 6 (Scans R 4921)

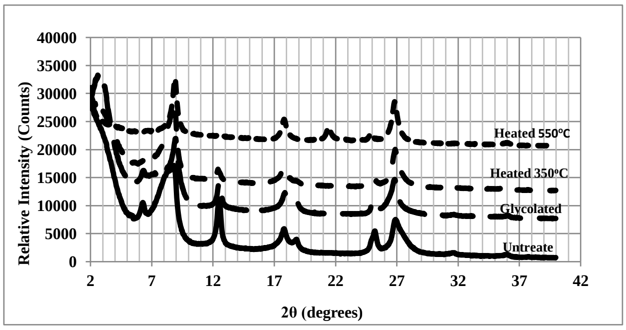

Figure 6: X-ray diffractograms of sample from Outcrop 8 (Scans R 4919)

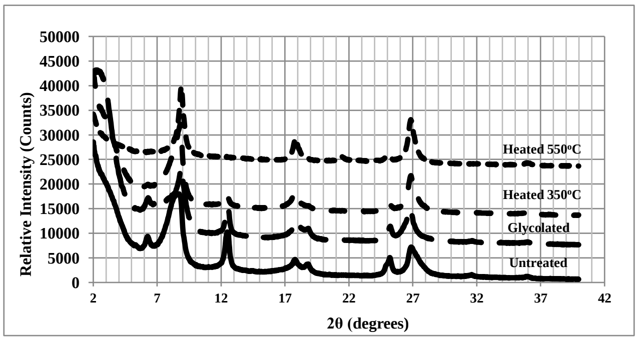

Figure 7: X-ray diffractograms of duplicate sample from Outcrop 8 (R 4922)

Table 8: Criteria for identification of clay (and non-clay) minerals in X-ray diffraction analyses. (After Thorez, 1975 and Poppe et al., 2001)

Clay Mineral	Primary Criteria	Additional Criteria
Kaolinite	Symmetrical peak at 7.15 Å (12.36° 2θ) on untreated, glycolated & 550°C heated scans. Not seen on 550°C heated scan.	Peak at 3.58 Å (24.88° 2θ) on untreated, glycolated & 350°C heated scans. Not seen on 550°C heated scan.
Illite	Asymmetrical peak at 10.02 Å (8.82° 2θ) on untreated, glycolated & 350°C heated scans. Becomes symmetrical peak on 550°C heated scan.	Symmetrical peaks at 5.01 Å (17.69° 2θ) & 3.34 Å (26.66°2θ) on untreated, glycolated, 350°C and 550°C heated scans.
Randomly Inter-stratified Illite-Mont-mrillonite	Diffraction band between asymmetrical peaks at 14.03 Å (6.30° 2θ) & 10.05 Å (8.80° 2θ) on untreated, glycolated & 350°C heated scans, Becomes single symmetrical peak at 10.05 Å (8.80° 2θ) on 550°C heated scan.	Symmetrical peak at ≈36.81 Å (2.40° 2θ) on glycolated scan, but convex curve at ≈3.11 Å (28.97° 2θ) on untreated & 350°C heated scans. Disappears in 550°C heated scan.
Non-Clay Mineral		
Quartz	Symmetrical peaks at 4.24 Å (20.87 2θ) & 3.34 Å (26.65 2θ) on untreated scan that do not shift in glycolated as well as 350°C & 550°C heated scans.	
Goethite	Low symmetrical peak at 4.18 Å (21.25° 2θ) on 550°C heated scan.	

Table 9: Clay sized minerals in mudstones from different outcrops along Jalan Sungai Hitam, Libaran, Sandakan

Outcrop	Scan Number	Clay minerals	Non-Clay	Relative Content
1 (Fig. 2)	R 4917	Randomly Interstratified Illite-Montmorillonite, Illite, Kaolinite	Goethite	RIM > I > K
1 (Fig. 3)	R 4920	Randomly Interstratified Illite-Montmorillonite, Illite, Kaolinite	Goethite	RIM > I > K
4	R 4068	Kaolinite, Randomly Interstratified Illite-Montmorillonite, Illite	Quartz	K > RIM > I
4	R 4077	Randomly Interstratified Illite-Montmorillonite, Kaolinite, Illite	Quartz	RIM > K > I
5	R 4071	Randomly Interstratified Illite-Montmorillonite, Kaolinite, Illite	Quartz	RIM > K > I
5	R 4073	Randomly Interstratified Illite-Montmorillonite, Kaolinite, Illite	Quartz	RIM > K > I
6 (Fig. 4)	R 4918	Illite, Randomly Interstratified Illite-Montmorillonite, Kaolinite	Goethite	I > RIM > K
6 (Fig. 5)	R 4921	Illite, Randomly Interstratified Illite-Montmorillonite, Kaolinite	Goethite	I > RIM > K
8 (Fig. 6)	R 4919	Illite, Randomly Interstratified Illite-Montmorillonite, Kaolinite	Goethite	I > RIM > K
8 (Fig. 7)	R 4922	Illite, Randomly Interstratified Illite-Montmorillonite, Kaolinite	Goethite	I > RIM > K

Note: I = Illite; K - Kaolinite; RIM = Randomly Interstratified Illite-Montmorillonite

5. Discussion

Results of the soil index tests show the sampled mudstones to have a low to high swell potential indicating the presence of swelling clay minerals. The liquid and plastic limits in particular, point to the medium to high swell potential, whilst the "activity index", based on the ratio of the plasticity index to the percentage content of fine clay (<0.002 mm), suggests that the mudstones are 'inactive'.

X-ray diffraction analyses show the clay minerals present to be kaolinite, illite and randomly interstratified illite-montmorillonite (a swelling clay mineral). In other outcrop areas of the Garinono Formation in eastern Sabah, in addition to kaolinite, illite, chlorite and interstratified illite-mica, the swelling clay minerals smectite and interstratified illite-smectite have been reported (Clennell. 1992). The presence of swelling clay minerals clearly indicates that mudstones of the Garinono Formation will be sensitive to atmospheric wet-dry cycles that can cause swelling and shrinkage (Xiao et al., 2017; 2018).

Repeated atmospheric wet-dry cycles with swelling and shrinkage will thus give rise to the desiccation cracks and fissures that will reduce the shear strength of the mudstones. Infiltration of water through these cracks and fissures during periods of rainfall will then lead to initiation of the slump-mudflows. These slump-mudflows will be of relatively shallow depths of up to about 2.5 m as this has been reported to be the depth of fissure development and atmospheric weathering in expansive clays in China (Xiao et al., 2017; 2018).

It is interesting to note that the presence of swelling clay minerals in the Garinono Formation in eastern Sabah was already recognized by earlier workers. Collenette (1966) for instance, more than 50 years ago, stated that the physical characteristics of the Garinono Formation were unusual and needed to be considered in any engineering project and resettlement scheme. Jacobson et al. (1970) furthermore, noted that the clay type present in the Garinono Formation in the Sungai Manila Settlement Scheme indicated that there might be a great loss in strength for a comparatively small increase in moisture content. In China, it has thus been recommended that stability analyses of slope cuts in expansive soils select shear strength parameters that consider the combined effects of wet-dry cycles and low stress (Xiao et al., 2017).

6. Conclusion

It is concluded that soil index properties, including the liquid and plastic limits as well as the clay (<0.0039 mm) and colloid (<0.001 mm) contents, point to the medium to high swell potential of the mudstones exposed at slope cuts along Jalan Sungai Hitam in Libaran, Sandakan. X-ray diffraction analyses show the clay minerals present to be kaolinite, illite and randomly interstratified illite-montmorillonite (a swelling clay mineral). Slump-mudflows that have occurred at the slope cuts are due to the randomly interstratified illite-montmorillonite which renders the mudstones sensitive to atmospheric wet-dry cycles. Repeated swelling and shrinkage has thus given rise to desiccation cracks and fissures which not only reduce the shear strength, but also allow infiltration of rainwater and initiation of the failures. It is also concluded that earthworks in areas of the Garinono Formation in eastern Sabah need to consider the presence of swelling clay minerals; an occurrence that can be inferred from evaluating soil index properties.

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