Characteristics of Hardpan Calcrete of the Nyalau Formation and Impact on Design of Foundations

A.C.Y. Sim[1], D.E.L. Ong[2], L.Y. Tai[3], W.H. Ting[4], E.P.S. Chai[5] and J. Bachat[6]
[1,2,5,6]*Jurutera Perunding Geoteknik Sdn Bhd*
[2]*Swinburne Sarawak Research Centre for Sustainable Technologies*
[3]*Jurutera Jasa (Sarawak) Sdn Bhd*
[4]*Consulting Engineer*
E-mail: anson.sim@jpgeoteknik.com

ABSTRACT: Nyalau Formation, found in Bintulu Division in Sarawak, Malaysia was formed by a thick array of shallow water marine and paralic sedimentary rocks. The formation is of predominantly sandstone origin and also the lesser known 'limestone' which is described as hardpan calcrete in this paper. Changes of sea levels during the mid-Pleistocene epoch resulting in the formation of raised terrace where marine deposits sedimented and subsequently followed by depositions of the coastal alluviums and inland peat swamps. The interaction of the depositions may have contributed to the formation of the hardpan calcrete. Laboratory tests such as petrographic thin section, X-Ray Diffraction (XRD), uniaxial compressive strength, point load tests, in-situ static load tests had been carried out on the hardpan calcrete to obtain the engineering design parameters to formulate a possible detailed design methodology on shallow foundation and its associated construction work progress. Several practical and effective solutions had also been proposed at locations where the hardpan calcrete layer was present. Use of finite element analyses in design has also successfully provided valuable in-sights into the complex soil-structure interaction.

KEYWORDS: Nyalau Formation, Hardpan calcrete, Shallow foundations, Foundation load tests

1. INTRODUCTION

Nyalau Formation of the Lower Miocene (Tertiary age) epoch (approximately 20 million years ago) found in Bintulu Division in the State of Sarawak, Malaysia, was formed by thick array of shallow-water marine and paralic sedimentary rocks. It is predominantly of sandstone origin and of the lesser known 'limestone', which this paper identifies as possible hardpan calcrete. The approximately 1m to 3m thick hardpan calcrete layer was found approximately 10m below ground and sandwiched between successive mudstone layers during the construction of shallow foundations of a large industrial plant at the newly-developed Samalaju Industrial Park. Within the calcrete, the eroded channels are infilled with soft clays, suggesting the karstic nature of the material. Based on the authors' extensive literature search that includes the resource centre of the local Minerals and Geoscience Department, so far, physical evidence of hardpan calcrete has not been documented in Sarawak, hence the need to develop further understanding on its formation and characteristics.

Koh (1968) postulated that the Late Tertiary and Quaternary (1.8 to 3.6 million years ago) bedrocks of Nyalau Formation was influenced by the changes of sea levels during the mid-Pleistocene epoch approximately 1.8 million years ago and resulted in the formation of raised terraces where marine deposits sedimented. This is subsequently followed by deposition of soil particles and/or organic matters forming the coastal alluviums and inland peat swamps at foothills, respectively. The interaction of changes in sea levels and sedimentation processes within the local landscape may have contributed to the formation of the hardpan calcrete.

Laboratory tests such as petrographic thin sections, X-Ray Diffraction (XRD), uniaxial compressive strength, point load tests, in-situ static load tests had been carried out on the hardpan calcrete encountered to obtain the engineering design parameters. A detailed methodology on shallow foundation and its associated construction process had been developed as a guideline. Several practical and effective solutions had also been proposed at locations where the hardpan calcrete layer was present. These include (i) combining individual pad footings to form a larger raft foundation system to reduce settlement potential if founding level is higher than possible calcrete level, (ii) "pile supported" shallow foundations on sloping sub-surface after calcrete removal and (iii) mass concreting over the hardpan calcrete layer after removal of soft clay infills. Use of finite element analyses in design has also successfully provided valuable in-sights into the complex soil-structure interaction.

2. GEOLOGICAL HISTORY OF BINTULU

Bintulu area has a unique stratigraphy as summarized in Table 1. The geological history of Bintulu can be clearly divided into two periods, namely the Tertiary/Neogene deposition and Quaternary deposition.

Table 1 Stratigraphy of the Bintulu Area (Koh 1968)

Age Classification		Sedimentary Rocks	Diastrophism and Conditions of Deposition
Quaternary	Holocene	Coastal, deltaic and riverine alluvium, mainly sand, silt, clay, and peat.	Deposition of alluvium Eustatic sea level changes Continued erosion
	Pleistocene	Terrace alluvium, mainly sand and silt, with some quartz gravel.	
Tertiary/ Neogene	Pliocene	Unconformity	Erosion followed by uplift Folding with some faulting
	Miocene	Sediments of Miocene age may have been deposited and subsequently removed by erosion	Shallow water marine deposition
		SETAP SHALE FORMATION: mainly shale and subordinate sandstone	
		NYALAU FORMATION: sandstone, shale, coal seams and thin lenses of limestone. Biban Sandstone Member at the base consist of hard sandstone and subordinate shale, with some thin lenses of limestone	Fairly rapid subsidence accompanied by shallow water marine deposition, and paralic deposition places

2.1 Tertiary / Neogene Deposition

The Miocene depositions possibly begin during the Oligocene times (23 million years ago) and prolonged up to the Miocene times which ranges between 5.3 to 23 million years ago (Koh 1968). The oldest deposition during the lower Miocene times, known as Biban

Sandstone member of the Nyalau Formation consists of hard sandstone and shale, with several layers of thin lenses of limestone. Sediments of Biban Sandstones were deposited in shallow-water marine conditions, littoral to inner neritic and accumulated close to shore along the shallow parts of the ocean.

Sedimentation in Miocene times were also deposited in shallow marine conditions where other types of Nyalau Formation rocks such as sandstone, and shale with coal seams and thin lenses of calcareous sandstones and limestones accumulated. Generally, Nyalau Formation consist of succession of hard, fine-grained, argillaceous, often calcareous, sandstones, in alteration with all possible gradations to shale and clay, and commonly lignitic (Lee *et al*., 2004). Sandy foraminiferal limestone lentils, and also limestone breccias consisting gastropods, lamellibranchs, and larger foraminifera occur frequently but hardpan calcrete have not recorded in the previous literature. .

With thickness of more than 3,000m of the Nyalau Formation, this illustrates the very quick subsidence in the time of sedimentation (Koh 1968). Liechti *et al*, (1960) stated the thickness of this rock formation is to be around 3,000 to 5,500m with exposed thickness of between 800 and 1,200m (Haile, 1962). Rapid subsidence has also resulted in development of extensive deltas and locally developed swamps which explain the existence of coal seams.

2.2 Quaternary Deposition

Older Quaternary sediments are deposited within the mid-Pleistocene. Terraces with gentle undulating surfaces were formed 10 to 15m above ground level, indicating that the formation is most probably not related to tectonic activities but Quaternary eustatic sea level fluctuation.

The terraces which are commonly found along the coast, consist of white to grey, unconsolidated sand and silt with quartz (Koh 1968). The terraces are generally known as terrace alluvium, where the thickness can vary from approximately 2 meters to as thick as 6m. In contact with the underlying sandstone are typically of terrace sand, stained dark-brown by humic compounds.

Humus podsols are usually accumulated on terrace alluvium, forming firm humus pan with varying depth from several centimetres up to 10m (Koh 1968). The infertile acidic and low permeability soil usually brings about perched water table above the terraces.

In the Holocene epoch, sand, silt and clay were deposited along coastal regions. Deposition of the recent alluvium comprises of eroded sandstone and shale from the Nyalau and Setap Shale Formations. Extensive peat swamps were also formed in recent times, where the peat can be up to 6m deep. The peat is typically water-logged, with high contents of partially decomposed vegetative matters.

3. HARDPAN CALCRETE

Hardpan calcrete can be categorized as a sedimentary rock close to surface, consisting of mainly calcium carbonate ($CaCO_3$). Calcrete are commonly formed by cementation of soil particles or ground-water evaporation. Caliche, synonymous with calcrete, are usually relatively impervious, sheet-like layers overlying softer or looser materials with rough upper surface and gradational lower surface. Unattached calcrete boulders and cobbles may be formed due to weathering or infiltration of groundwater. Similar to calcrete hardpans, distinct calcrete boulders are commonly hard to very hard and has rounded upper surface (Krug 1995).

Hardpan calcrete encountered at Samalaju Industrial Park, located approximately 62 kilometres north-east from Bintulu may have been formed within the terrace alluvium during the mid-Pleistocene epoch. A series of sea level changes may have caused layers of sand, silt and quartz gravels deposits from high sea level periods to be trapped in between deposits of the eroded Nyalau and Setap Shale Formations from low sea level periods as described in Table 2.

Table 2 Deposition of various materials due to changes in ancient sea levels

Changes of Sea Level	**Postulated Geological Activities**
Low Sea Level	a. Deposition of eroded materials from Nyalau and Setap Shale Formation. b. Subsidence of deposited sediments
High Sea Level	a. Deposition of sand, silt and quartz gravels from the rise of sea level. b. Subsidence of deposited sediments
Low Sea Level	a. Deposition of eroded materials from Nyalau and Setap Shale Formation above the deposits from high sea level – trapped sediments from high sea level forms calcrete due to mechanical and chemical reactions. b. Subsidence of deposited sediments

Hardpan calcrete samples were retrieved from Samalaju Industrial park and sent for Hand Specimen, petrographic thin section (Figure 1) and X-Ray Diffraction (XRD) test (Figure 2). Results of Hand specimen describes the sample as hard, fine-grained, dark grey in colour and reacts vigorously with 10% hydrochloric acid.

The petrographic thin section results shows that the sample is fine-grained and made out of fine calcite minerals, silt-sized quartz grains (5%) and some carbonaceous materials. Fossils of algae and skeletal remains of marine organisms (Figure 3) can also be observed in the matrix. The content of hardpan calcrete from the petrographic thin section is similar to the deposited materials during the Pleistocene Epoch as described by Koh (1968).

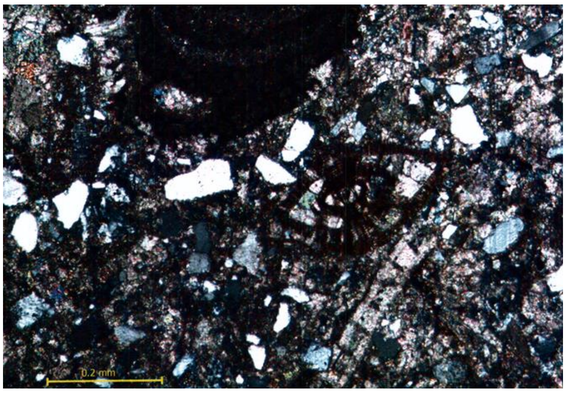

Figure 1 Petrographic thin section of hardpan calcrete

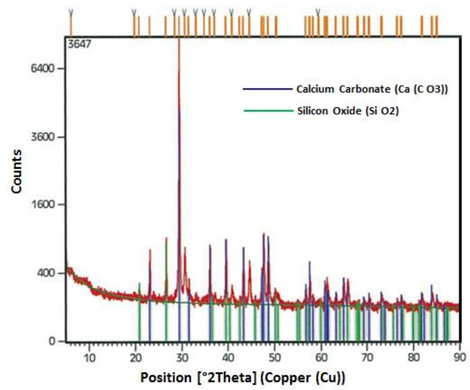

Figure 2 Mineral identification by XRD technique

Figure 3 Marine fossils present on the hardpan calcrete

The sample is found to constitute of mainly calcium carbonate and silicon dioxide (Quartz) from an element composition test with WD X-Ray Flourescence Spectrometer (WD-XRF) Technique as shown in Table 3. Test results reflect the definition of calcrete by Krug (1995), "A term for terrestrial materials composed dominantly, but not exclusively of calcium carbonate". From the tests carried out, it is thought that the uncommon rock matrix found in Samalaju Industrial Park is hardpan calcrete.

Table 3 Composition of elements of hardpan calcrete

No.	Element Formula	Conc. (%)
1	O	18.217
2	Na	0.110
3	Mg	1.336
4	Al	2.208
5	Si	5.912
6	S	0.445
7	K	0.603
8	Ca	65.811
9	Ti	0.188
10	Mn	0.331
11	Fe	4.305
12	Sr	0.390

3.1 Physical Properties of Hardpan Calcrete

The hardpan calcrete found in Samalaju Industrial park has similar physical properties as both sanstone and limestone. This calcium carbonate cemented matrix is generally light-coloured, but can range from white to light pink to reddish-brown, depending on the amount of impurities present (Oklahoma Department of Mines, 2011). Hardpan calcrete layers can vary from a few centimeters to a few meters thick and multiple layers can exist in a single location as shown in Figure 4.

Hardpan calcrete layer has relatively low permeability, which leads to possible formation of perched water table. Groove line features are commonly found on the upper surface of hardpan calcrete as shown in Figure 5. The groove lines may be the result of reactions between the slightly acidic ground water or perched water table, eroding the hardpan calcrete. Clayey materials have been observed along the groove line features that derived from the erosion of mudstone, and trapped in the hardpan calcrete layers due to the impermeable mudstone below.

Chemical tests on the water samples collected during sub-surface investigation works show that the pH level for ground water at Samalaju Industrial Park ranges between pH 6.0 to 6.3. The slighlty acidic ground water may be due to the presence of peat swamps formed in recent times (Uchida & Hue 2000).

Hardpan calcrete layers encountered were observed to be filled with a relatively soft, wet, very sticky and unusually plastic material known as marl as shown in Figure 6 (Moxham & Eckhart, 1956). According to Blatchley (1900), marl is a soft earthy material mainly consisting of clay and calcium carbonate or lime. The colour of marl ranges from milky-white to brownish yellow, dependent on the precentage of impurities the marl contains.

Marl at the Samalaju Industrial Park should have high clay and calcium carbonate contents due to erosion of both hardpan calcrete and mudstone layers. The mixture of dissolved calcrete and weathered materials may be the possible cause of soft marl materials infilling the impervious hardpan calcrete.

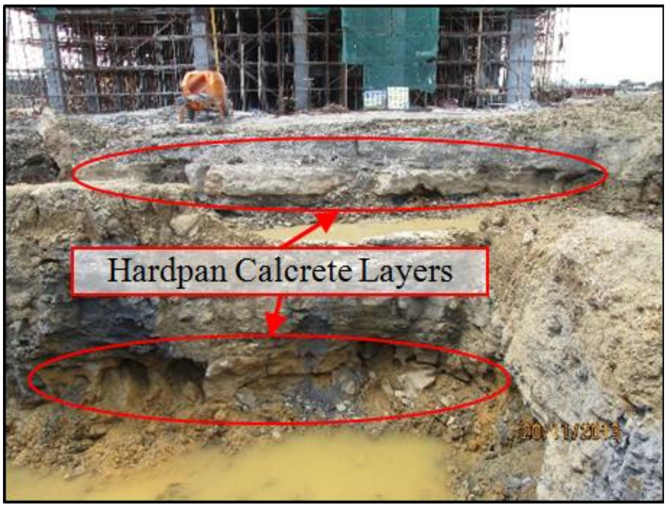

Figure 4 Hardpan calcrete layers

Figure 5 Features of hardpan calcrete

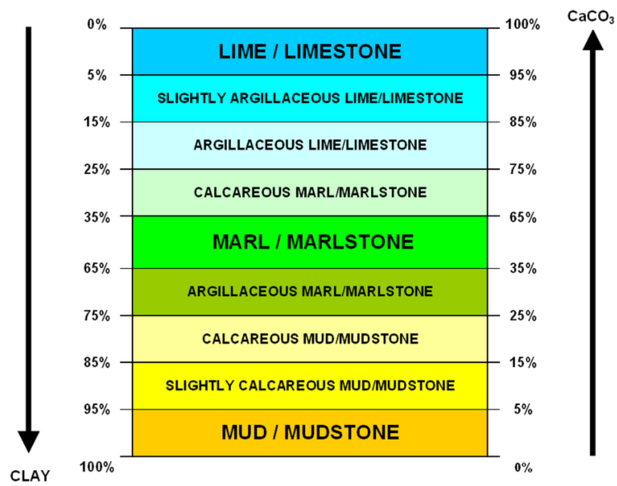

Figure 6 Clay and $CaCO^3$ content of different materials

4. GEOTECHNICAL CONSIDERATIONS AND SOLUTIONS

The geotechnical design for this project at Samalaju Industrial Park consists of several major components, namely sub-surface investigation, interpretation of ground condition, foundation design and foundation test. The sub-surface investigation comprised 200 boreholes, 21 seismic refraction lines and laboratory tests carried out to understand as much as possible the inherent ground condition and to obtain reliable design parameters.

A foundation design scheme as shown in Figure 7 was formulated in order to set up a proper procedure for engineers to execute during design and construction works. The undulating nature of the Nyalau Formation requires a mixture of both shallow and deep foundations (but not on the same building) in this project. Shallow foundations for this project consist of raft foundations and pad footings, whereas deep foundation comprises of driven piles only.

According to the design scheme, foundation tests were carried out during the initial foundation construction stage in order to verify the performance of the designed foundations. Foundation construction works was only carried out progressively after foundation tests results had verified the required design capacity.

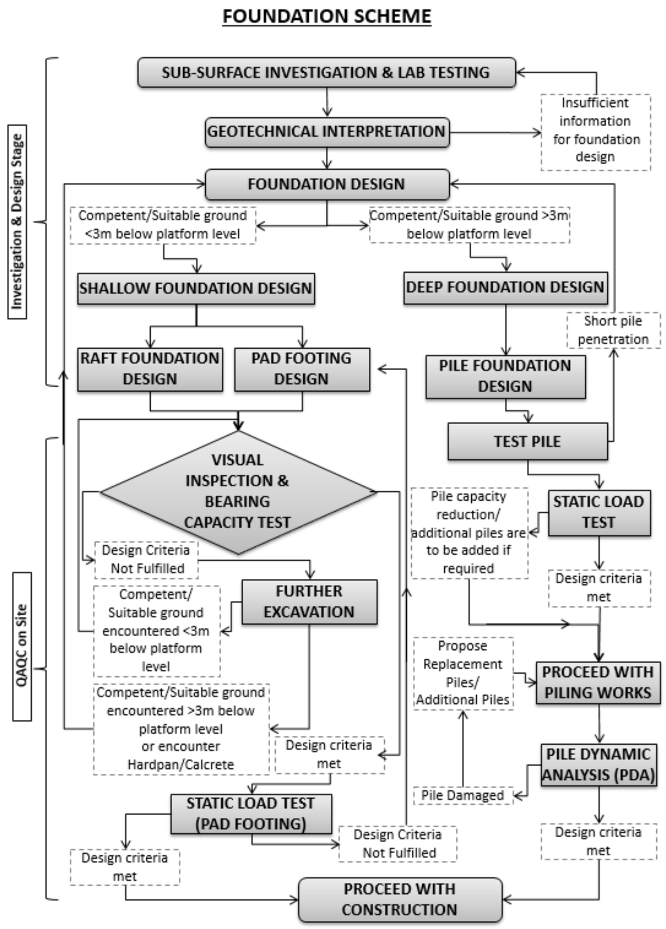

Figure 7 Flowchart on foundation design adopted

4.1 Foundation Tests

Foundation verification tests carried out for this project includes dynamic cone penetration test (CPT) (GB 50021-2011 – Code of China), Constant Rate of Penetration (CRP) Test, Maintain Load Test (MLT) and Pile Dynamic Analysis (PDA), according to BS8004. CPT tests were carried out on all shallow foundation locations before foundation construction work can be carried out. Generally, if the ground immediately beneath was found to have insufficient bearing capacity, further excavation will be carried out until the founding layer with required bearing capacity is found before replacing the excavated material with mass concrete.

Static load tests, comprising CRP and MLT were carried out with the kentledge system. The selected foundations were tested to twice working load in order not to exceed the structural capacity of the foundation structures (Singapore Standards 2004). A total of three static load tests were selected and compared in this paper. Selected static load tests comprise load test for 300mm spun pile, 500mm spun pile and a 1.6 m x 2.2 m pad footing, where the results are tabulated in Table 4. The ground condition for each static load test interpreted from the nearest borehole is shown in Figure 8.

Table 4 Results of kentledge load tests

		300mm Spun Pile	**500mm Spun Pile**	**Pad Footing 1.6m x 2.2m**
Foundation working load (Tonnes)		60	116	145
Pile penetration (m)		5.7	6.9	-
Constant Rate of Penetration Test (CRP)	Settlement at working load (mm)	20.35	2.87	9.62
	Settlement at twice working load (mm)	46.86	5.89	11.64
	Residual settlement after removal of twice working load (mm)	43.62	1.19	6.99
Maintained Load Test (MLT)	Settlement at working load (mm)	-	2.45	4.27
	Settlement at twice working load (mm)	-	6.91	5.83
	Residual settlement after removal of twice working load (mm)	-	1.72	0.85

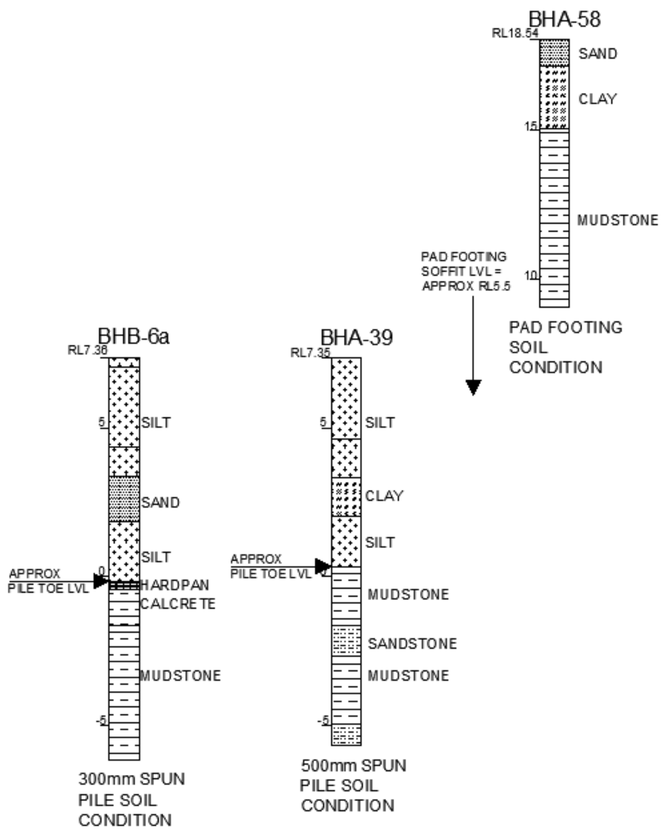

Figure 8 Soil profile at kentledge load test location

Deducing from the settlement readings of CRP it is clearly indicated that the ground where the 300mm spun pile is driven into is unable to support the load applied. The settlement recorded exceeded the limiting values specified by Jabatan Kerja Raya (JKR) Malaysia – 1988, where pile settlement at twice working load should not be more than 38.0mm or 10% of the pile diameter or width.

The cause of this phenomenon was not further investigated with additional exploratory boreholes or field tests due to time constrain. The possible presence of the hardpan calcrete (Figure 8) with marl infill at the end bearing layer for the pile may be a possible cause of the relatively large settlement. The load applied on the pile may have been transferred onto a thin layer of hardpan calcrete with soft marl infill underlying it, resulting in a large residual settlement after each load cycle. Laboratory results for hardpan calcrete specimens shown in Table 5 reveal that the complex matrix has very high compressive strength. The behaviour of a possibly thin brittle layer of calcrete with underlying soft marl deposits is unknown, which may be a possible reason of the 46.86mm settlement recorded at twice working load of the pile. As a solution, the design capacity of the 300mm spun pile was downgraded from 60 tons to half the capacity, 30 tons. Based on the plot in Figure 9, settlement recorded at 30 tons is relatively small and the settlement at twice working load of 30 tons, 60 tons, is within the limiting values specified by Jabatan Kerja Raya (JKR) Malaysia – 1988.

Table 5 Compressive Strength of Hardpan Calcrete

Sample Ref	Sample Dimensions: Diameter, mm	Sample Dimensions: Height, mm	Load at Failure, kN	Unconfined Compressive Strength, N/mm^2(15.5Is)	Is, MPa
UCS Specimen A	55.58	109.47	151.71	62.53	-
UCS Specimen B	55.45	109.99	186.40	77.20	-
PLT Specimen A	55.54	-	17.20	86.49	5.58
PLT Specimen B	55.35	-	20.50	103.70	6.69

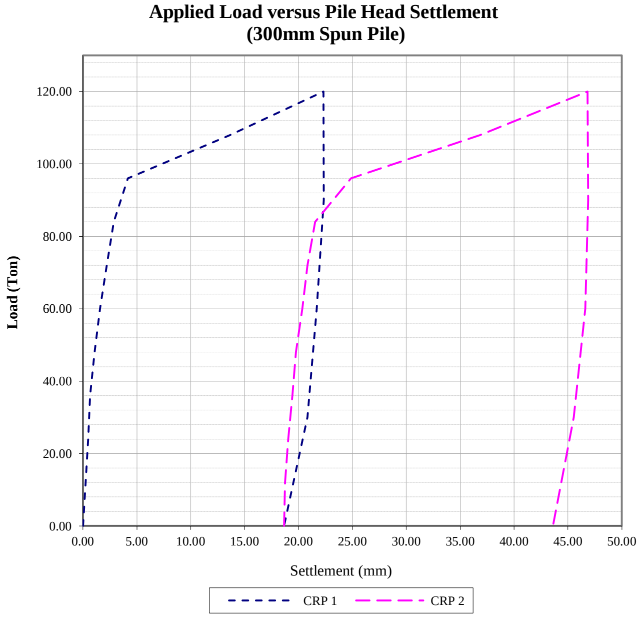

Figure 9 Load-settlement behaviour of 300mm spun pile

On the other hand, results for the 500mm pile CRP test (Figure 10) and 1.6m x 2.2m pad footing (Figure 11) fulfills the JKR specifications but shows very different settlement behavior when test load is applied.

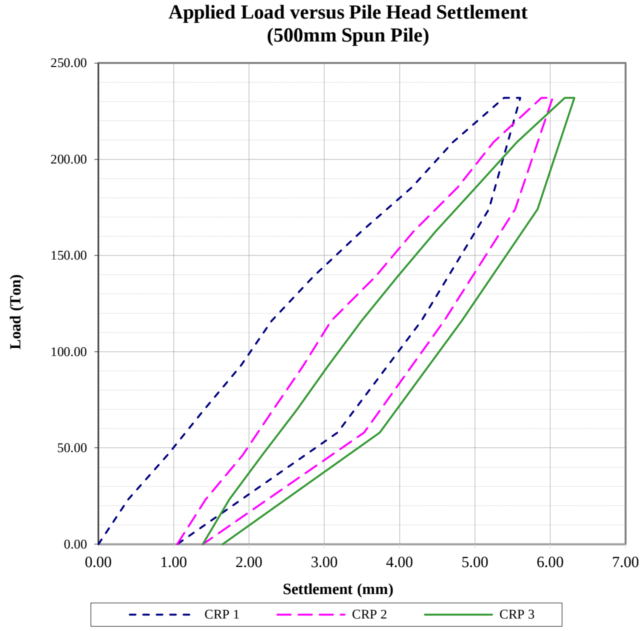

Figure 10 Load-settlement behaviour of 500mm spun pile

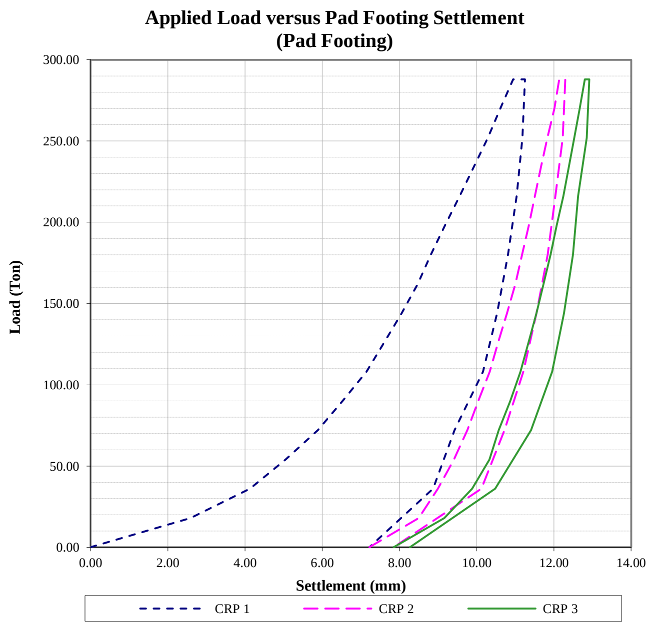

Figure 11 Load-settlement behaviour of pad footing

The CRP Test for 500mm spun pile shows a relatively higher magnitude of pile head settlements with increasing load when load was initially applied to the pile. A gentler gradient of settlement was observed towards the end of the test showing that the skin friction may have been fully mobilised thus, load is transferred to the end bearing of the pile. The graph also indicates that the pile behaves elastically as the residual settlement decreases for every cycle, which is expected for a good pile foundation (Chin 1978).

Dissimilar from the spun pile, the pad footing shows a different behavior of settlement during the CRP Test. As shown in Figure 11, larger magnitude of settlement was observed during the initial stage followed by lesser settlement towards the end of the test. The higher magnitude of settlement may be the result of immediate settlement from the uneven surface area or poor surface preparation of the pad footing.

Settlement was recorded to be smaller as compared to initial stage as the applied pressure may have caused mobilisation of bearing pressure of the ground after immediate settlement had taken place (Bengt 1999). This is further proven by subsequent CRP results mainly CRP2 and CRP3 which shows no indication of immediate settlement and almost full rebounds of the plate after load removal.

4.2 Geotechnical Engineering Solutions for Difficult Ground Conditions

Several foundation locations were found to be located at areas with hardpan calcrete. Hardpan calcrete with grooves filled with marl may cause undesirable damages due to possible differential settlement. In avoiding possible risk or structural damage, calcrete layers in loose boulders and hardpan calcrete layers that are relatively thin (30cm to 40cm) were excavated and backfilled with mass concrete. Massive layers of hardpan calcrete that has thicknesses between 1.0 m and 3.0 m were further analysed and with possible solutions designed.

One of the designed solutions was to combine three individual pad footings that are located on a hardpan calcrete layer. A site exploration for the three pad footings as shown in Figure 12 was carried out by drilling seven holes to investigate the probable thickness of hardpan layer and presence of marl infill beneath the uneven layer. The reason for carrying out this exercise is to explore possible solutions other than removing the relatively thick and solid layer of hardpan calcrete because it can be an expensive and time consuming process.

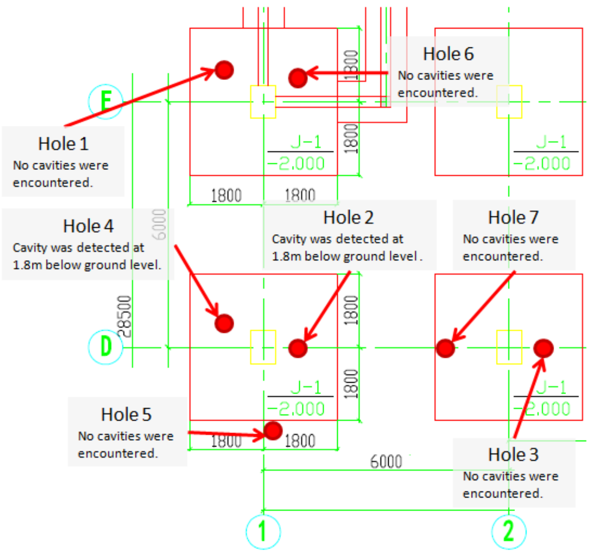

Figure 12 Investigation holes peformed to verify presence of hardpan calcrete

The investigation identified a soft marl layer that was 1.8 m beneath the footing at gridline 1/D. The findings were from the drilling results of hole nos. 2 and 4 as shown in Figure 12. The drilling probe was observed to have plunged into a soft layer with high moisture content after 1.8 m of drilling, causing soft marl to ooze out from the drilled holes and the probe jammed in the drilled hole. The other five holes were drilled up to 5.0m depth without encountering any cavities.

The hardpan layer was found to be approximately 2.8 m thick. This is confirmed by the observation of the drilled material/dust flushed out from the drilled hole after every 0.2 m to 0.3 m of drilling. In order to rectify this problem, a combined footing was designed to form a larger contact area to spread the designed load that was initially required for pad footing 1/D. The combined footing shown in Figure 13 also acts as a rigid pad to decrease any possible differential settlement. A finite element analysis was carried out across section B as shown in Figure 14. Figures 2 and 16 show the analysed stresses acting on the pad footing and the settlement respectively for considering presence of cavity.

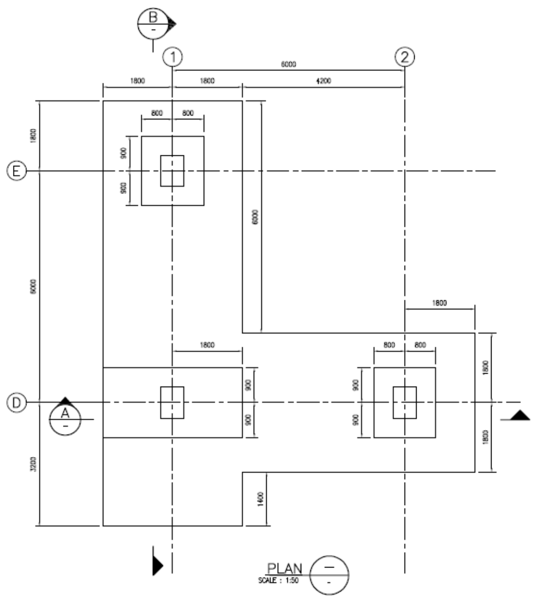

Figure 13 Re-designed combined pad footings

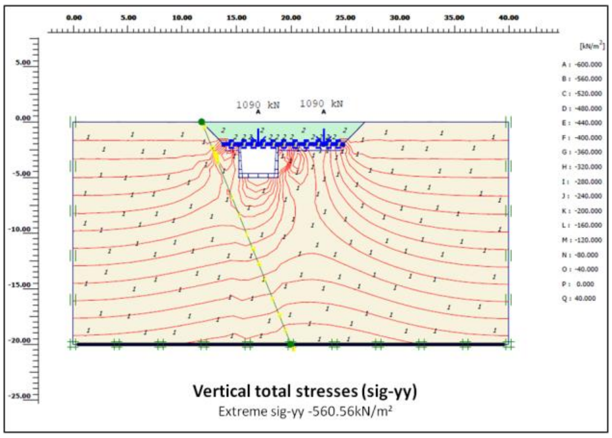

Figure 14 Finite element model with presence of cavity

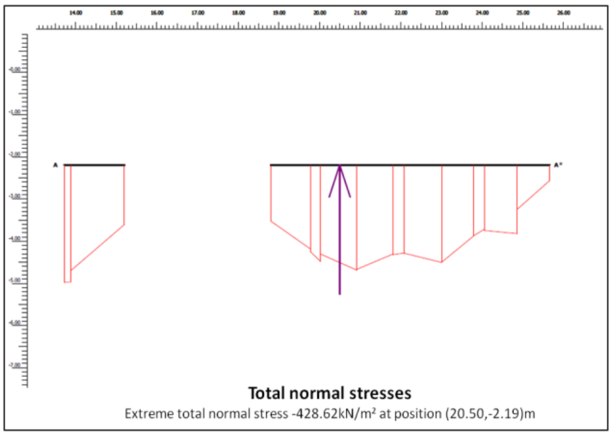

Figure 15 Analysed stresses acting on pad footing considering presence of cavity

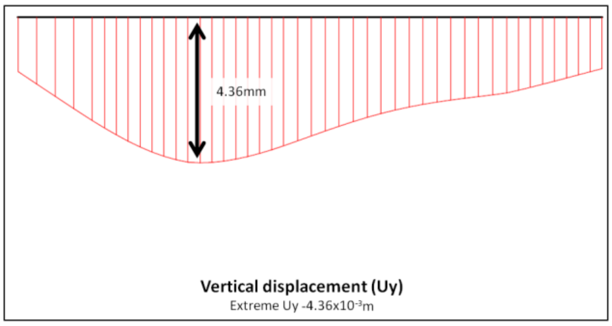

Figure 16 Analysed settlement considering presence of cavity

The combined pad footing was modelled as a plate element, which sits directly above the soft marl infill. Another assumption made was that all the grooves or cavities present on the upper part of the hardpan calcrete layer will be cleaned thoroughly and backfilled with mass concrete before the combined pad footing was to be constructed over it. Thus, the calcrete layer with grooves backfilled with concrete is assumed as a layer with higher compressive strength that will experience minimal settlement, hence the applied load can be transferred underlying rock layer effectively. Conservatively, the cavity was modelled as void infilled with ground water.

The total normal stress computed by the finite element analysis is 428.62kN/m^2 whereas the extreme vertical displacement is 4.36mm. According to Bjerrum and Meyerhof's admissible and danger limits as shown in Table 6, a maximum of 4.36mm settlement over 6.0m span falls within the 1/750 angular distortion criteria (8mm over 6m) indicating that there will be minimal settlement to a structure and will not interrupt operation of sensitive machineries (Ricceri & Soranzo n.d.).

Table 6 Admissible and danger limits (Bjerrum and Meyerhof)

Angular Distortion (Slope)	**Damage or Allowable Criteria**
1/750	Limit where difficulties with machinery sensitive to settlement are to be feared
1/600	Limit of danger for frames with diagonals
1/500	Safe limit for buildings where cracking is not permissible (safe limit for reinforced load-bearing walls)
1/300	Limit where first cracking in panel walls is to be expected; limit where difficulties with overhead cranes are to be expected
1/250	Limit where tilting of high, rigid buildings might become visible (danger limit for panel walls of frame buildings and reinforced load-bearing walls; safe limit for open steel storage tanks and tilt of high rigid structures)
1/150	Considerable cracking in panel walls and brick walls; safe limit for flexible brick walls with h/L ¼); limit where structural damage of general buildings is to be feared (danger limit for open steel and reinforced concrete frames, steel storage tanks and tilt of high rigid structures; safe limit for statically determine structures and retaining walls)
1/100	Danger limit for statically determinate structural and retaining walls

As more hardpan calcrete layers were being exposed on site, a finite element model was set up with Plaxis V8 to study the possible magnitude of settlement if pad footing was constructed over the soft marl infills present in between the mudstone and hardpan calcrete layers. The purpose of this study is to investigate the minimum thickness of mudstone layer required as cover above a marl infill in order to achieve the 1/750 angular distortion criteria in Table 6 (Ricceri & Soranzo n.d.). Anything thinner will require the excavation to remove the calcrete and the soft marl before backfilling it with mass concrete. The sequence of finite element is shown in Figure 17.

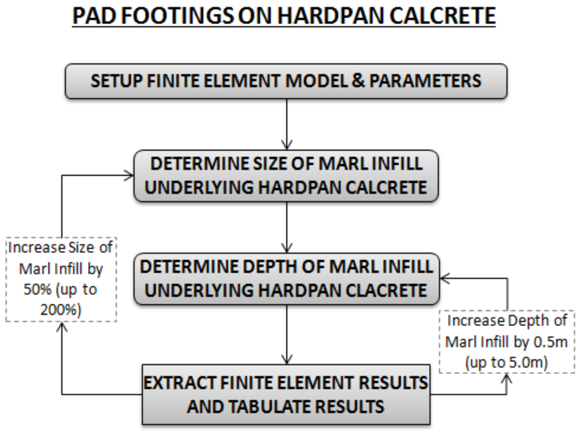

Figure 17 Procedure to analyse shallow foundation on hardpan calcrete with underlying marl infill

This method of investigation is necessary when pad footings are founded on mudstone layers where hardpan calcrete layers with marl infill were encountered while constructing surrounding pad footings. Several holes should be drilled with a percussion hand drill to investigate the presence or depth of marl infill beneath the mudstone layers where pad footing will be founded on.

The analysis was carried by assuming a marl infill is present with various sizes and depth within a homogeneous mudstone layer. Hardpan calcrete layers are not modelled as the relatively hard material beneath the marl infill should not impact the results greatly. Soil properties similar to a SPT-N 15 soil were utilized to model the marl infill within the mudstone layer. Properties of the mudstone layers were obtained from the laboratory test result carried out during the sub-surface investigation stage. An axis symmetry model with equivalent surface area as a 2.2 m x 1.6 m pad footing was used for the parametric study.

The main intention for the analysis is to understand the minimum thickness of mudstone layer required to found a pad footing which can safely spread the load to the underlying layer. An angular distortion limit of 1/750 was selected for the parametric study as the structure that will be constructed will most likely be housing equipment that are sensitive to ground subsidence.

Results of the analysis revealed that both depth factor and width factor of the marl infill affect the magnitude of settlement of the pad footing, as shown in Table 7 and Figure 18 respectively.

Table 7 Finite element analysis results

Depth of Marl Infill Beneath Pad Footing	**Settlement Induced in Relation to Size of Cavity (mm)**			
	50% of Pad Footing Width	**100% of Pad Footing Width**	**150% of Pad Footing Width**	**200% of Pad Footing Width**
No Cavity	4.33	4.32	4.35	4.36
-0.50	5.62	7.88	**8.45**	**8.73**
-1.00	4.90	6.56	7.11	7.38
-1.50	4.70	5.84	6.42	6.66
-2.00	4.60	5.51	5.84	6.13
-2.50	4.53	5.17	5.47	5.63
-3.00	4.42	4.92	5.03	5.16
-3.50	4.36	4.47	4.63	4.70
-4.00	4.33	4.34	4.40	4.45
-4.50	4.34	4.33	4.39	4.38
-5.00	4.33	4.32	4.36	4.37

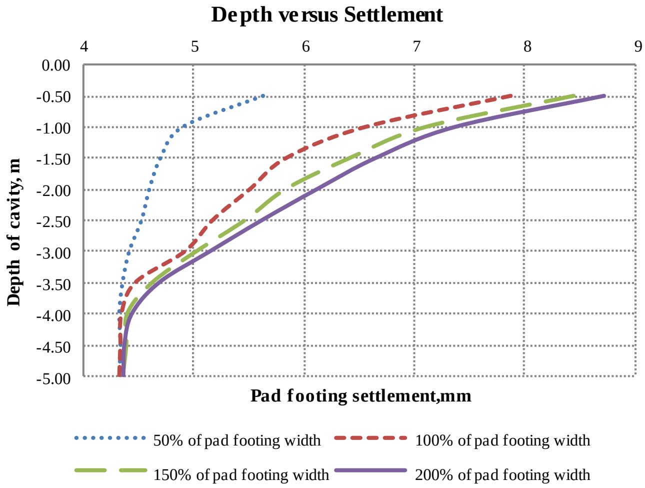

Figure 18 Analyzed relationships between depth of cavity and settlement of pad footing

The magnitude of settlement was observed to be decreasing with depth for all the analysis with different width of marl infill. This finding also aligns with the concept of a pad footing where pressure applied is uniformly distributed from the pad footing. As a result, the magnitude of settlement for marl infill at a lower depth was observed to be smaller.

Therefore, the findings from this finite element analysis reveals that, a minimum thickness of 1.0m of mudstone is required above the hardpan calcrete layer in order to prevent differential settlement issues that may cause disruption to equipment that is sensitive to ground subsidence.

Other than hardpan calcrete, the undulating terrain of the project site is also a challenge where that requires various design consideration to construct shallow foundations. The undulating terrain has bedrock that can vary from very gentle gradient to terrains with 70° to 80° slopes. Piled foundations are not feasible as short pile penetration length will lead to problems such as low pile capacity and pile tilting issues. Pile capacity from short piles is relatively low due to minimal contribution from skin friction. Insufficient lateral response from surrounding soil because of short penetration depth will be a problem where any small magnitude of soil movement would push the pile top to deflect and pile toe to kick back causing it to tilt.

The utilization of mass concrete to even out steep slopes of competent ground surface was one of the solutions adopted to cater for the undulating ground as shown in Figure 19. The mass concrete method will be utilized when bedrock/suitable ground is located less than 3.5m deep from the proposed soffit level of the pad footing.

Mass concrete is a preferred replacement material compared to compacted suitable soil as the compaction effort as well as the compatibility of the soil stiffness may be an issue due to the poor weather condition. Mass concrete is also a faster solution that will have minimal water ponding issues that may deteriorate the easily weathered rock before a replacement material is placed.

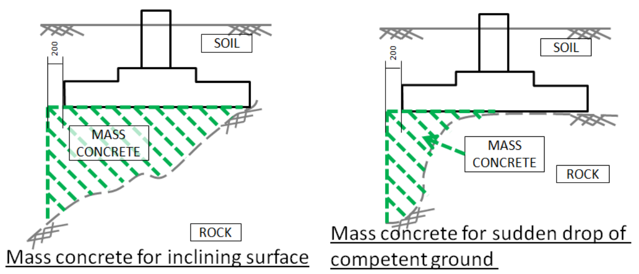

Figure 19 Schematic of mass concrete for pad footing supported on undulating rock profile

In conditions where competent ground is more than 3.5 m deep from the pad footing soffit level, a pile supported pad foundation system shown in Figure 20 will be adopted. The driven piles in a mat pattern act as ground improvement method that provides similar bearing capacity required by the pad footing design. Pile capacity for the driven piles were designed as short piles where the governing capacity for the pile is the end bearing capacity with minimal or no contribution from the skin friction. The spacing of the piles can be determined by equation below.

$$\therefore l_{pile\ spacing} = \sqrt{\frac{Pile\ capacity}{Ground\ \ Bearing\ \ capacity\ \ required}}\ \text{(in meter)} \quad (1)$$

The reinforcement of the driven piles are not joint to the pad footings, instead, the pile heads are flushed against the soffit and tied together by the 100mm thick lean concrete. The reason for this design is to allow the pad footing to behave like surrounding pad footings where the load from the pad foundations are evenly transferred to the underlying hard stratum by the closely knitted mat piled system.

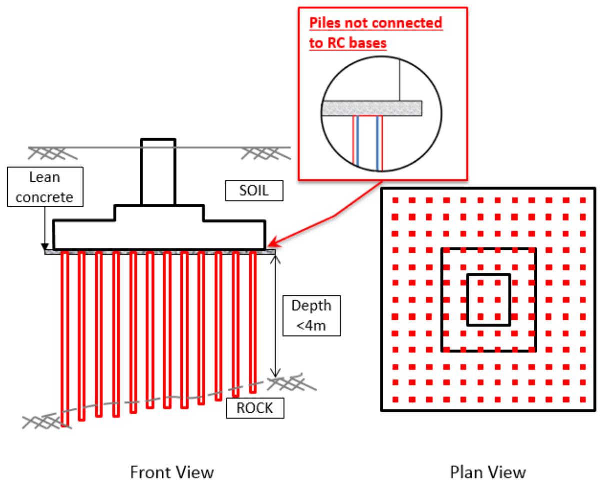

Figure 20 Schematic of 'pile-supported' pad footing for ground with overburden less than 4m

5. CONCLUSION

Hardpan calcrete might have been formed during the mid-Pleistocene epoch as a result of the formation of terrace alluvium where mainly sand and silt, with some quartz gravel were sedimented and subsequently followed by depositions of inland peat swamps. This phenomenon has created a difficult ground condition for foundation works to be carried out. The relatively hard and brittle cemented rock with soft infills are unsuitable for foundations to be supported on without additional ground treatment methods. As shown in one of the static load tests, the pile that was suspected to be sitting on the hardpan calcrete layer was not able to achieve the design load without exceeding the maximum allowable settlement.

One of the solutions to this problem is to reduce the load applied on the cemented material by reducing the pile capacity or enlarging the pad footings. A finite element analysis in this paper also shows that a pad footing can be founded on ground condition with underlying hardpan calcrete if a layer of mudstone with minimum thickness of 1.0m is present above the hardpan calcrete. The mudstone or materials with equivalent strength will allow the load from the pad footing to be uniformly distributed, leaving a relatively low pressure that the hardpan calcrete with marl infill can withstand without major deformation.

6. REFERENCES

Bengt H. F. (1999) Bearing capacity of footings and piles – A delusion?, *DFI Annual Meeting*, Dearborn, Michigan.

Blatcheley, W. S. (1900) *Geology and Natural Resources*, Indianapolis Ind, p40.

British Standards Institution (1986) *Code of practice for foundations*, BS 8004, BSI, London.

Chin, F. K. (1978) Diagnosis of pile condition. *Geotechnical engineering*. Vol. 2.

GB 50021—2001, *Code for Investigation of Geotechnical Engineering 2009 Edition[S]*. Beijing: China Architecture & Building Press.

Haile, N. S. (1962) The geology and mineral resources of Suai-Baram area, North Sarawak. *Geol. Surv. Mem*., 13, p176.

Kho, C. H. (1989) *Geological Survey Borneo Region, Malaysia: Bintulu area, central Sarawak, East Malaysia*, Government Printing Office, Kuching, Sarawak.

Krug, M. A. (1995) *Geochemical Exploration in Calcrete Terrains*, Department of Geology (Mineral Exploration), Rhodes University, Grahamstown, South Afica.

Lee, C. P., Leman, M. S., Hassan, K., Nasib, B. M. and Karim, R. 2004. *Stratigraphic Lexicon of Malaysia*. Geol. Society of Malaysia, p162.

Liechti, P, Roe, F. W. and Haile, N. S., 1960. The geology of Sarawak, Brunei and the western part of North Borneo. *Geol. Surv. Bull.,* 3, vol. 1, p360.

Moxham, R. M. and Enchart, R. A. (1956) *Marl Deposits in the Knik Arm Area Alaska*, United States Department of the Interior.

Oklahoma Department of Mines (2011), *Annual Report 2011*, Oklahoma, Department of Central Services Central Printing.

Ricceri, G. & Soranzo, M. (n.d), *An analysis on allowable settlements of structures*, p197.

Singapore Standards (2003) *Code of practice for foundations,* CP 4 : 2003, SPRING Singapore.

Uchida, R. & Hue, N. V. (2000) Soil acidity and liming, Plant nutrient management in Hawaii's soils, *Approach for Tropical and subtropical agriculture, College of Tropical Agriculture and Human Resources*, University of Hawai at Manoa, pp10-101.