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One-Dimensional Consolidation of Kelang Clay

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ABSTRAK

Satu kajian mengenai kelakuan pengukuhan lempung Kelang dibentangkan dalam kertas kerja ini. Sampel tanah yang diambil dari kawasan yang berhampiran dengan Pelabuhan Kelang menunjukkan bahawa lempung tersebut boleh dibahagikan kepada lempung marin di sebelah atas dan lempung sungai di sebelah bawah. Perbezaan awal ini adalah berdasarkan kehadiran kelompang laut pada bahagian atas dan bahan ini tidak didapati pada lapisan bawah. Telah ditunjukan bahawa kedua lempung ini mempunyai ciri pengukuhan serta lain-lain ciri geoteknik asas yang berbeza. Sejarah pengukuhan menunjukkan bahawa lempung Kelang adalah terkukuh normal dan dikelaskan sebagai lempung kebolehmampatan tinggi. Tekanan tanggungan atas akibat tanah tambak mestilah diabaikan untuk memperolehi nisbah pengukuhan lebih yang sebenar. Telah didapati juga bahawa sekaitan yang diberikan oleh Terzaghi dan Peck (1967) memberikan anggaran yang terbaik bagi index mampatan terutamanya bagi lempung marin.

ABSTRACT

A study on the consolidation behaviour of Kelang clay is presented in this paper. The soil samples taken near the Port of Kelang showed that the clay can be divided into upper marine and the lower river clays. The initial distinction was based on the existence of sea shells in the upper deposits and none in the lower deposits. It has been shown that these two clays have different consolidation properties as well as other basic geotechnical characteristics. Consolidation history indicated that Kelang clay is normally consolidated and may be classified as a high compressibility clay. The overburden pressure due to fill must be neglected in order to obtain the true overconsolidation ratio. It was also found that the correlation given by Terzaghi and Peck (1967) provided the best estimates for the compression index, particularly that of the marine clay.

Keywords: consolidation, Kelang clay, marine clay, river clay, Malaysian clay, Malaysian soil

INTRODUCTION

The rapid growth of industrialisation requires an extensive construction of infrastructure in Malaysia. In addition to new projects, the maintenance and upgrading of facilities also provided significant input to the overall development. Some of the major areas that are receiving impetus for such developments include the coastal regions where ports and highways are located. These areas of quartenary age consist mainly of soft clays, peat and other soft organic deposits. It poses major construction and maintenance problems due to low bearing capacity and high deformation behaviour (Chin 1967, Mustafa and Wan Badaruzzaman 1989, and Mohamad and Chin 1990).

In general, theory of consolidation deals with the response of soil systems to imposed load and predicts stresses and displacements of the loaded soil as a function of space and time. This theory, since its introduction by Terzaghi in 1923, has formed the foundation of modern geotechnical engineering. The concept is fundamental to the practice of geotechnical engineering where the interaction of soil and water dominates. Although consolidation is used for estimating settlements, it has also played key roles in analysing stability of slopes, design of piled foundations, laboratory tests, etc. (Schiffman *et al.* 1984).

An extensive study has been undertaken to study, characterise and predict the bahaviour of Kelang clay. This was undertaken so that future structures can be designed and constructed safely and economically. The consolidation study presented in this paper formed part of the goals towards achieving this endeavour.

Site Geology and Basic Geotechnical Properties

Generally, the thickness of the soft clay deposits in the Southeast Asian region (which includes countries such as Malaysia, Indonesia, Singapore, Thailand, etc.) ranged from very shallow thin layers to depths of 40 m. It is then followed by layering of sand, peat and other soft clay deposits finally reaching the quartzite bedrock at about 80 m below the surface (Cox 1970; Ting and Chan 1971; Bibi 1971; Ting and Ooi 1977; and Bosch 1988). These deposits were formed about 10,000 years ago due to change in sea level. The geological environment for the rise and fall of sea level in Peninsular Malaysia was elaborated on by Tjia (1975 and 1977).

DATA

The soil sample used in this study was obtained near the port of Kelang. In the Kelang area, the soft clay deposits ranged between 20 to 40 m in thickness (Bibi 1971). Below these layers of sand, clay and organic deposits follow. At certain locations, the organic deposits may reach 6 m in thickness. A similar profile was observed some 200 km to the north along the coast (Britt and Ratcliff 1970).

RESULTS AND DISCUSSION

A borehole profile of the subsurface soil is shown in *Fig 1.* In actual fact two clay layers existed in the profile, i.e. marine and river clays. They are differentiated by the existence of corals and sea shells which is the distinguished feature of the marine clays (Ahmed 1992). The sea shells were found to increase in number with depth until 15.8 m where the marine species formed a boundary of about 10 cm thick. Below this depth no marine specimens were observed. Small wooden chips and decayed roots were traced throughout the borehole. Thin layers of sand/silt were also found in the river clay.

Most clays are either greenish or bluish in colour except in the upper 2.25 m which are dark gray in colour. The gray colour was possibly developed due to oxidation of sulphur and iron in the clay as a result of it being exposed to atmosphere. Dennet (1932) observed that the in-situ blue clay turned to gray and finally reddish-yellow in 9 months. The existence of the dark gray clay at depths of 18 m, 21 m, and 24 m illustrates the deposition of the clay layer with respect to the dramatic rise and fall of sea level beginning some 10,000 years ago (Ahmed 1992). The clay fractions for both deposits ranged between 27 to 48%. The main clay minerals were montmorillonite (42%), illite (24%), kaolinite (21%) and microcline (13%). The microline is a mineral which will eventually turn to kaolinite giving the total kaolinite 34%.

The index properties of the Kelang clay are also shown in *Fig 1.* The average values of the Atterberg's limits and unit weights are given in Table 1. The water contents of the marine clay were very close to the liquid limit with all liquid limit values below 84%. In the Casagrande's plasticity chart, the soil fall in the left CH (high plasticity clays) region with most points lies just above the A-line. The river clays have liquid limits in excess of 84% and are located on the right CH region. Similar observations were made by Jaadil (1991).

TABLE 1
Average values of some geotechnical properties of Kelang clay

Clay type	Water content w_n (%)	Liquid limit LL (%)	Plastic limit PL (%)	Unit weight kN/m^3	G_s
Marine	71	71	32	15.48	2.64
River	88	103	41	14.42	2.61

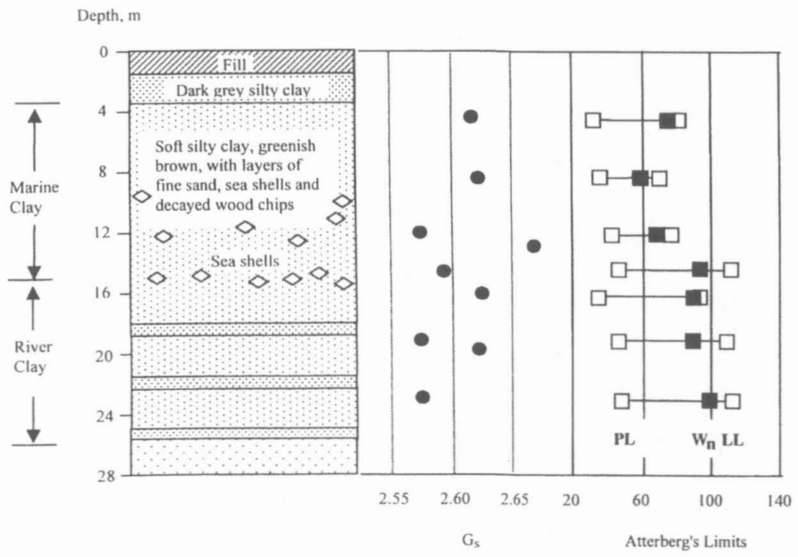

Fig 1. Depth profile, specific gravity (G_s) and Atterberg's limit of the clay deposit

Consolidation Behaviour

Fig. 2 shows a typical plot of *e-log* σ_{vc} curve of the marine clay sample. It illustrates a slightly concaving curve as it reaches the virgin compression line demonstrating some sensitivity. Vane shear test results indicated a sensitivity value of 1.7 to 6.5 indicating low to medium sensitive clays.

The typical consolidation curve of the river clay is shown in *Fig. 3*. It also shows a concave upon reaching the virgin line. For both clays, beyond the preconsolidation pressure, the compressibility decreases continuously with the increase in effective vertical stress. The main difference to that of the marine clay is that the initial void ratio of the river clay is significantly higher. The coefficient of volume change, m_v which increases and then reduces in the virgin line is the same for both clays. The coefficient of consolidation, c_v, also decreases after reaching the past maximum pressure, σ_{vm}. This indicates that the sample is not disturbed or slightly disturbed. Thus the approximation of the σ_{vm} can be considered reliable.

Consolidation test parameters for all tests are given in Table 2. The values of σ_{vm} and c_v were obtained using the Casagrande's method. The c_v and m_v parameters are the mean values in virgin compression. The table is divided into two because it was initially assumed that the upper marine clay and the lower river clay have different properties. This table provides further proof to this hypothesis. The compression and rebound indices (C_c and C_s, respectively) for river clay are twice those of the marine clays. The modified compression and rebound indices ($C_{c\varepsilon}$ and $C_{s\varepsilon}$, respectively) show that the values are consistent or almost constant for the upper marine clay. However, it increases with depth for the river clay. This analysis omits the results for depth of 15.65 m because the values obtained were way off line due to difficulties in obtaining the void ratio caused by the existence of many sea shells.

TABLE 2
Results of 1-D consolidation tests

Depth (m)	C_c	C_r	m_v (m^2/MN)	c_v (m^2/yr)	σ'_{vc} (kPa)	$C_{c\varepsilon}$= C_c/(1+eo)	$C_{r\varepsilon}$= C_r/(1+eo)
4.09	0.610	0.102	0.49	1.55	34	0.2	0.045
8.10	0.525	0.098	0.47	3.51	45	0.2	0.045
12.28	0.587	0.113	0.48	6.03	90	0.205	0.047
Average	0.574	0.111	0.48	3.70			
15.65	1.102	0.249	0.66	0.48	105		
16.10	0.705	0.164	0.51	0.55	100	0.20	0.05
19.10	0.934	0.262	0.52	0.45	110	0.27	0.075
23.01	1.049	0.311	0.54	0.50	130	0.305	0.09
Average	0.947	0.246	0.56	0.49			

The c_v values show that marine clay have significantly higher values compared to that of river clay. It is possible that high c_v of the marine clay is due to the fine sand layers. However, the m_v values show similarities with the river clays

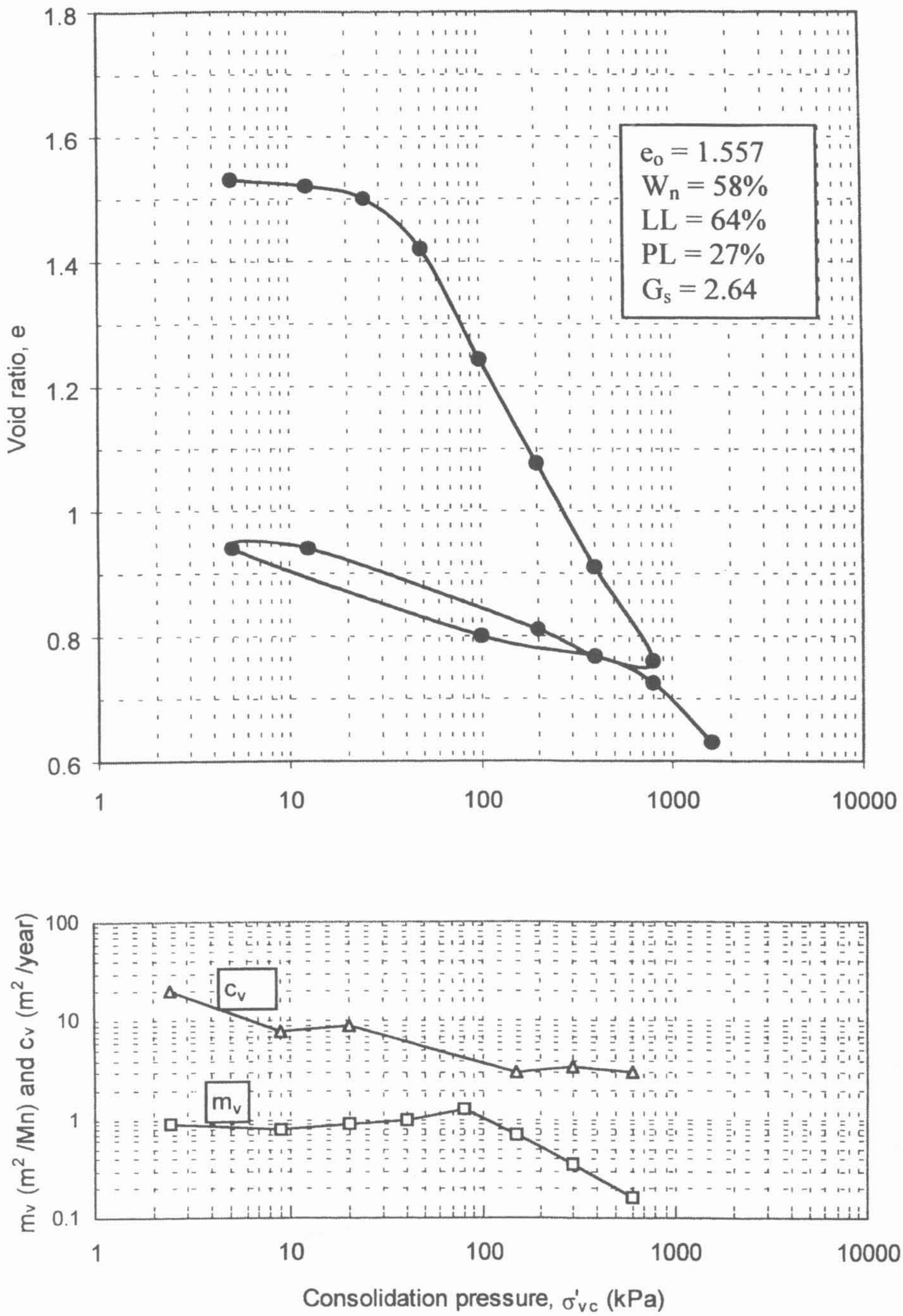

Fig 2. Consolidation test results for samples at 8.10 m

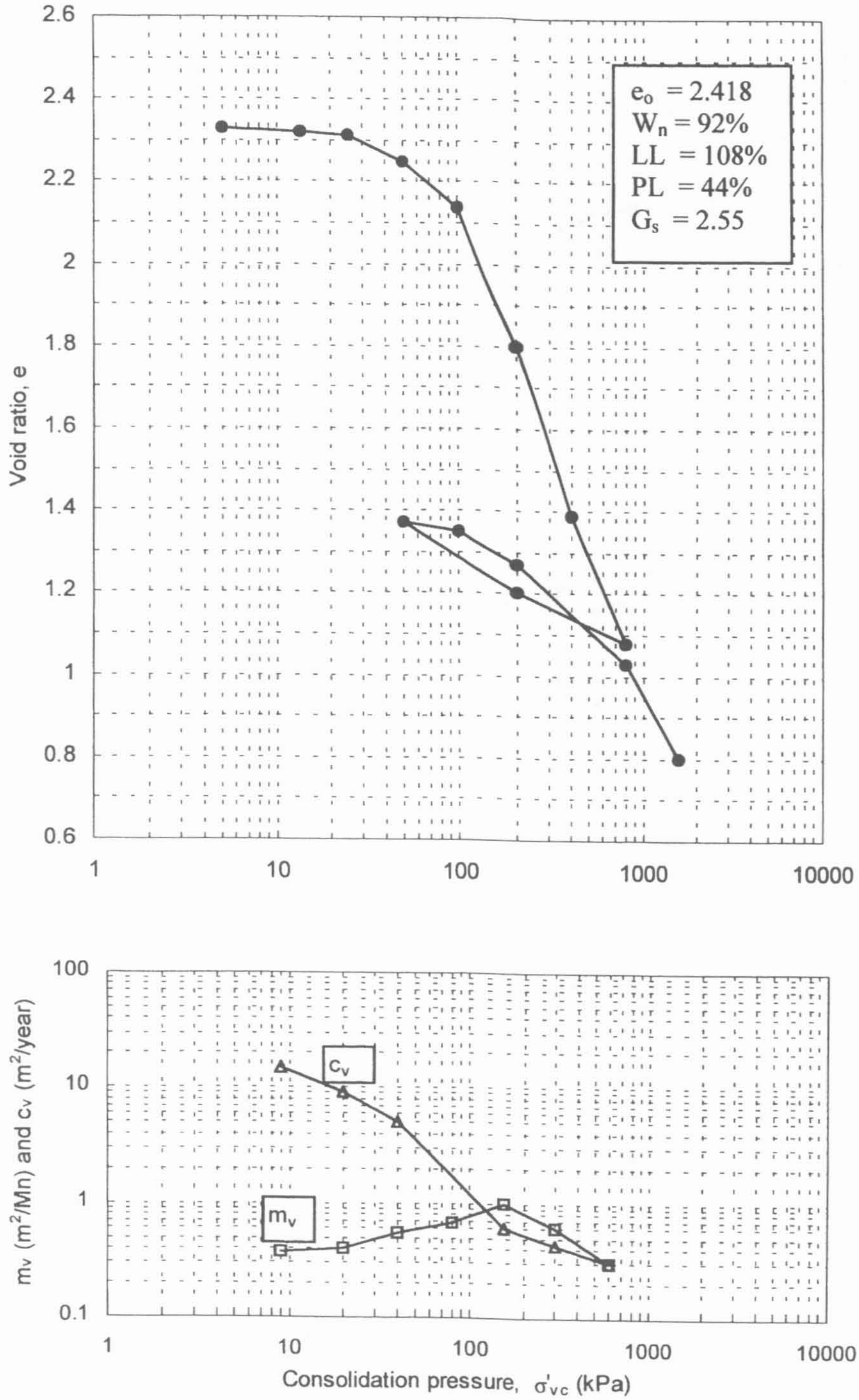

Fig 3. Consolidation test results for samples at 19.10 m

having higher indices. Based on Head (1984), Kelang clays (marine and river clay) may be classified as clay with high compressibility and it is most probably a normally consolidated clay.

Estimation of Consolidation History

Fig. 4 shows the plot of past maximum pressure, σ'_{vm}, against depth. The two white circles represents minimum and maximum probable values and the black circles represent the most probable values. These are estimated from *e-log* σ'_{vc} plots at the respective depths (Ahmed 1992). The overburden pressure, σ'_{vo} was calculated based on assumptions that the groundwater table is at 2.3 m and using unit densities from Table 1. The line on the right is the calculated σ'_{vo} incorporating filled areas and the left is without the fill. It can be seen that σ'_{vm} may lie anywhere on and between these two lines.

In order to predict which line represents the actual σ'_{vo}, *Fig. 5* (US Navy, 1971) illustrates the correlation between c_v and LL that has been used. Using LL, *Fig. 1* and c_v in Table 2, the results obtained showed that the samples were practically undisturbed. In general, there was no remoulding and all points lie above the line for remoulded samples (refer to *Fig. 5*). One point, however, is located outside/above the upper line, indicating a probable overconsolidation. This is the value which lies close to the right line (depth 12.28 m). Since all other σ'_{vm} are closer to the left line except two points, the more appropriate line which represents σ'_{vo} is the left line, *i.e.* the line which ignores the fill. However, it must be mentioned that the fill should not be ignored especially

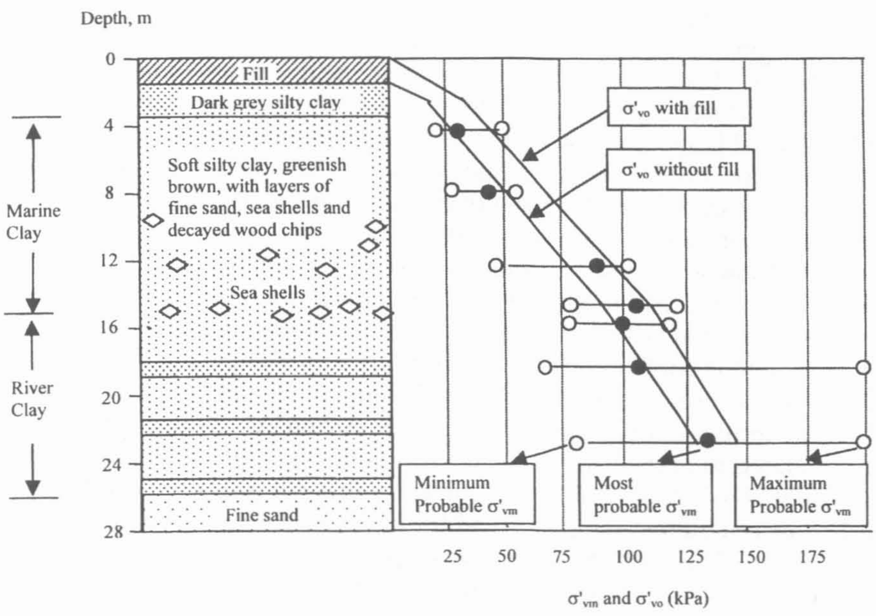

Fig 4. Estimation of σ'_{vm} and σ'_{vo} of Kelang clay

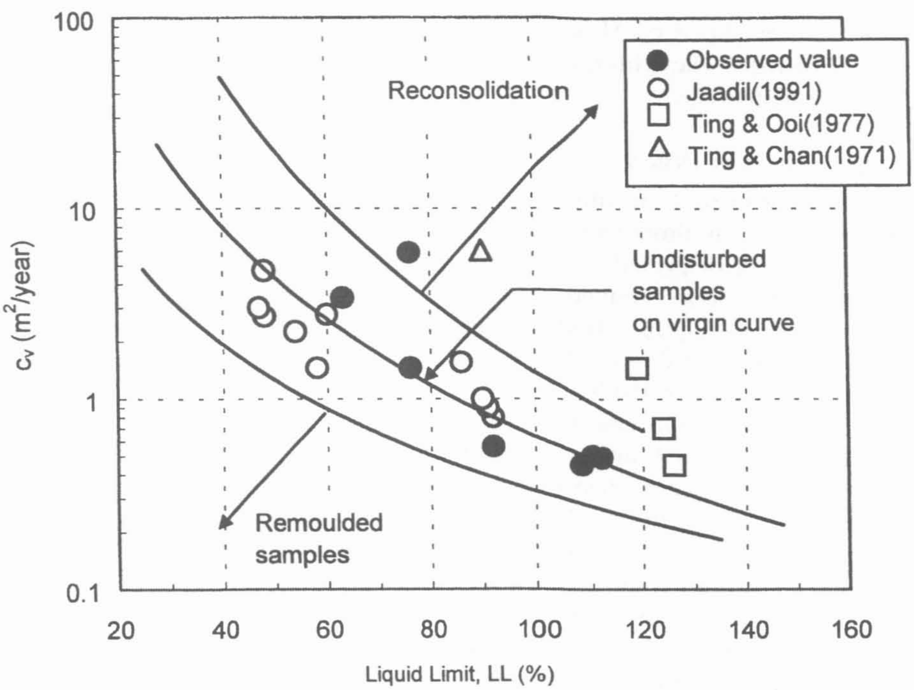

Fig 5. Relationship between c_v and LL (after U.S. Navy1971)

when one is calculating the settlement. Thus, it must also be realised that the clay is still undergoing consolidation under the weight of the fill.

The existence of overconsolidated deposits at 12.28 m and 15.65 m is not surprising. The change in sea level (Fairbridge 1961) made it possible that there existed a stable coastal beach at this depth sometime in the past. Thus, these depths were previously near the surface. Desiccation (drying) and consolidation, that usually occur near the surface, could have possibly resulted in overconsolidation. Other processes that may attribute to overconsolidation include underdrainage, minor erosion of sediments and chemical changes caused by precipitation and oxidation, such as cementation and colouration of the clay (Terzaghi *et al.* 1996). It is also possible that the deposits may have achieved complete consolidation due to sand layers in the profile.

The σ'_{vo} line chosen resulted in the establishment of the fact that Kelang clay is a normally consolidated clay as opposed to being probably underconsolidated as previously reported (Ting and Chan 1971; Ting and Ooi 1977 and Jaadil 1991). It is possible that the consolidation tests were conducted on disturbed or remoulded samples. In addition, when the data from Ting and Chan (1971) and Ting and Ooi (1977) were plotted in *Fig. 5*, the results fell into the reloading zone (overconsolidated). On the other hand the results of Jaadil (1991) showed that the clay was in the undisturbed zone indicating normally consolidated soil. Jaadil (1991) conducted the *LL* tests on oven dried soil which might have affected the results. All three researchers also have the *e-log* σ curves indicating remoulded samples, i.e. lines which do not curve as it approaches the virgin compression and does not show a clear σ'_{vm}.

Compression Index Relationships

There are many empirical relationships between compression index and basic soil properties such as water content, initial void ratio, liquid limit and plasticity index. The relationships can provide a quick estimation of the compressibility of clay prior to complete results from consolidation tests. By far, the most common formula links compression index and liquid limit and only a few of these models will be discussed in this paper. The earliest relationship between compression index and liquid limit was provided by Skempton (1944). The formula was based on test on remoulded clays and is not appropriate for comparison. Thus, it will not be used for further discussion.

Terzaghi and Peck (1967) obtained a relationship for normally consolidated clay with low to medium plasticity such that:

$$C_c = 0.009\ (LL\text{-}10) \tag{1}$$

This relationship is shown in *Fig. 6*. For the data obtained in this study, it can be concluded that the formula is excellent for LL up to 110%. Beyond this, the relationship underestimates C_c. Since the water content of the marine clay is lower than 84% and river clay more than 84 %, therefore the formula will have a better correlation for the marine clay. In general, however, since the formula has a reliability of about 30%, it can be concluded that the formula fits very well for Kelang clay.

Huat *et al.* (1995) obtained the following relationship for clay in the region of west coast of Selangor (Kelang is located in this zone):

$$C_c = 0.005\ (LL{+}71.8) \tag{2}$$

This line has also been plotted in *Fig. 6*. It does provide a good estimation of the C_c; however, it can be observed that the correlation provided by Terzaghi and Peck (1967) gives a better estimate of this consolidation parameter.

CONCLUSION

The consolidation tests and analysis conducted in this study indicated that the Kelang clay is normally consolidated as opposed to earlier findings that it is underconsolidated. Furthermore, the clay is divided into the upper marine and the lower river clays. The existence of sea shells in the upper deposits distinguished the two profiles. Test results also indicated that the upper marine clay has a sensitivity range of low to medium. It has a significantly lower initial void ratio compared to that of the river clay. The compression and rebound indices of the river clay are also higher for the river clay indicating greater total compressibility of this deposit. The coefficient of consolidation, however, showed that it is significantly higher for the marine clays. Analysis of data

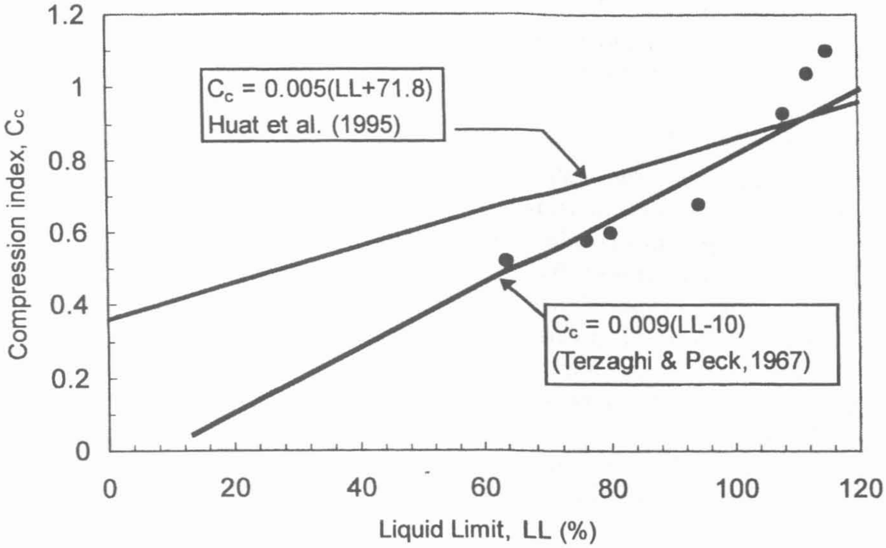

Fig 6. Relationship between C_c and LL

revealed that the relationship provided Terzaghi and Peck (1967) gives an excellent estimate for the compression index from liquid limit values particularly that of the marine clay. Similarly, relationship forwarded by Huat *et al.* (1995) also provided good estimates.

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