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ROADS ON PEAT IN EAST SUMATRA

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SYNOPSIS

The geotechnical constraints and foundation design of a road, capable of carrying heavy axle loading, through an environmentally sensitive region of Sumatra Indonesia is described. The road sub-base materials comprise highly compressible thick peat deposits overlying soft clay. A primary requirement of the design was that the road construction should not significantly modify the water table level in the peat or disrupt drainage paths. This was stipulated to minimise the fire risk, avoid affecting the existing ecosystem and the possibility of regional settlement of the peat surface. In addition, to control flooding the road surface was required to be 0.5m above ground level. A suitable design was found to be a timber piled raft combined with geogrid reinforced stone pavement.

INTRODUCTION

Indonesia has one of the largest land areas of peat in the world; estimates of the total area vary between 18 and 26 million hectares with 8 million hectares of peat over 2m deep (Euroconsult, 1984).

A substantial part of these peat deposits are found along the east coast of Sumatra, an area now being developed as a result of oil and gas finds.

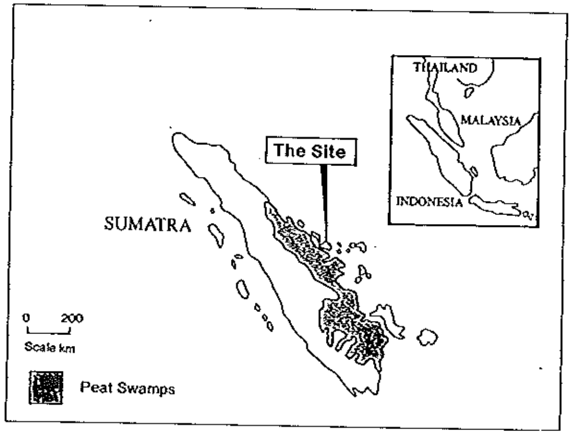

Fig. 1 Peat Swamps in Sumatra

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LASMO Oil are developing oil and gas fields on Padang and Tebing Tinggi Islands, which lie offshore East Sumatra, and which have up to 11 m of peat overlying soft recent marine clay. The extent of peat swamp deposits in Sumatra (after Whitten et al, 1987), and the location of the LASMO exploration area, are shown on Fig. 1.

The LASMO development has included the construction of roads and hardstands for camps, access to wellheads and other uses. As a result of settlement and flooding of the initial roads, LASMO commissioned a detailed study of the engineering properties of the ground conditions, in order to identify satisfactory construction methods. The engineering requirements had to meet environmental criteria set out by LASMO, as identified from their studies of the peat forest on the islands.

Whilst much is known of the engineering properties of temperate climate peat, and in particular the comprehensive summary of Hobbs (1986), there is very little published information on peats formed in the tropics. This paper describes the engineering and environmental information on the peat, the contraints this applied to the engineering design, and the designs ultimately adopted.

ENVIRONMENTAL ASSESSMENT

Padang Island lies immediately offshore of the mainland of Riau Province, Sumatra. It is some 60km in length by 24km in width at its widest point. The area of the study is the southern part of Padang Island together with the northern tip of the adjacent Tebing Tinggi Island.

The ground rises from the coast of Padang Island at a slope of generally 1 in 200 to some 8m above mean sea level. Above the 8m contour, which is 2 to 4km inland, the ground is essentially flat, rising to 9m and occasionally 10m elevation, with lower lying areas down to 4m in the middle of the island. With limited drainage and flat terrain there is a high ground water table, and areas of standing water or swamp. The flattened dome shaped topography is typical of the ombrogenous[1] peat formations found in Sumatra and Kalimantan.

Large forested areas on the deep peat of Padang Island and the neighbouring Tebing Tinggi Island have remained relatively intact, particularly when compared with the large extent of forest damage on mainland Sumatra. Approximately 74% of Padang Island remains covered with primary forest, and secondary forests account for a further 19%; only the remaining 7% is occupied by settlements, plantations and open agricultural areas. The large extent of intact forest is due mainly to the poor fertility of the peat; this condition has limited agricultural activities and, as a result of the stunted trees over the deep and infertile peat, has also limited commercial forestry.

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[1] see Appendix for peat classification terms

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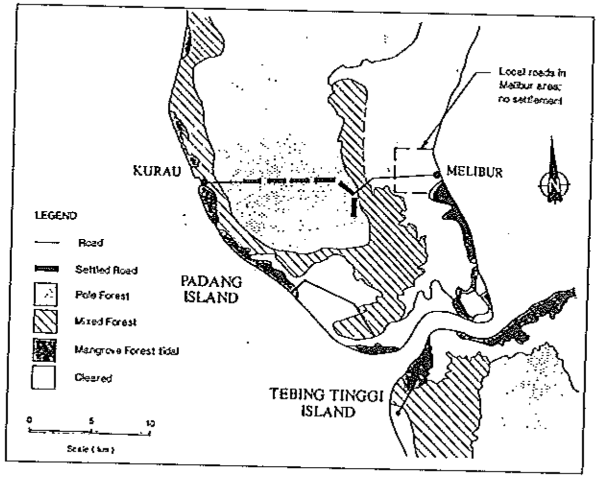

Fig. 2 Forest Areas on Padang Island

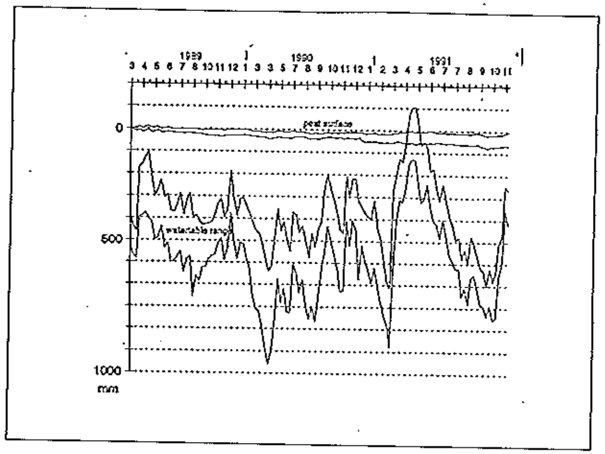

Fig. 3 Variations in Groundwater Level in the Peat

The forest areas, assessed from aerial photographs and field reconnaissance, are shown on Fig. 2. The two main types of forest are the mixed forest areas near the coast, and the pole forest areas inland; the latter can also be subdivided into high pole forest, medium pole forest and stunted pole forest, differentiated on infra-red satellite imagery as tonal variations, thought to represent declining leaf area of the forest canopy.

A detailed description of the forest areas has been given by Brady & Kosasih (1991).

There are significant differences in the peat of the pole forest and that of the mixed forest. The pole forest peat contains a substantial mat of very weak roots to a depth of 0.4m and is completely fibrous by visual inspection. After deforestation the surface of the pole forest peat is very compressible and it is possible to sink in up to above the knee even when the water table is low. The mixed forest peat on the other hand is more hemic to sepric in texture (that is, less fibrous), and contains occasional pieces of timber which cannot easily by broken by hand.

Groundwater levels fluctuate seasonally from ground level to one metre below the ground surface. A typical set of monitoring data are shown on Fig. 3.

PEAT FORMATION

Morley and Flenley (1987) suggest that the kinds of historical events leading to the initiation of coastal peatland in the tropics are environmental changes of three main types: sea-level changes; changes in rainfall quantity and seasonality; temperature changes. A climate without a pronounced dry season and high rainfall were considered by Kostermans (1985) as being necessary for the large scale peatland development that occurred on the east coast of Sumatra. Both Payette (1988) and Starkel et al (1991) propose that hydrological balances in temperate peatlands have changed since their initial development. Their studies suggest that high temperatures and associated high rainfall initiated peat development thousands of years ago. Since then temperatures and rainfall have declined, but the lower evapotranspiration rates associated with the temperature drop have maintained the peat formations.

After the last glacial maximum, 18000 years before present (BP), sea-levels in S.E. Asia rose rapidly and reached their present levels near 6000 BP (Williams, 1985). Tija (cited in Whitten et al, 1987) estimates that 6000 BP sea-levels in Sumatra were 3.5 m above current levels and declined slowly since then. Sea-level decline must have been a dominant factor in the formation of the vast alluvial plain along the entire east coast of Sumatra 5000 BP (Verstappen, 1973) and peat initiation very soon after. According to Diemont (1987) peat began accumulating along the east coast of Sumatra about 4800 BP. Silvius et al (1984) studied peatlands in the Berbak Reserve in Jambi Province, Sumatra. They mention the possible occurrence of coastal uplifting prior to peat initiation to explain the presence of higher than present sea-levels. The peat-clay boundary is currently found between high water level and mean water level in South Sumatra (Ministry of Public Works, 1984). Current sea-levels have little effect on the hydrology of peat formations except for erosion of peat adjacent to the coast.

Temperatures were also lower during the last glacial maximum with sea-surface temperatures being 2-3°C below todays temperatures (Whitten et al, 1987). From about 12000 to 5000 BP temperatures increased in Sumatra. As a result the glaciers in the Gunung Leuser mountains melted between 14000 and 7590 BP (Morley and Flenesly, 1987). Temperature data for Sumatra for the past 5000 years are not available, but extrapolating from other regions of the tropics it appears that temperatures were higher than present, similar to tropical Australia (Williams, 1985) and tropical South Asia (Dickinson and Virji, 1987).

Rainfall was higher and the wet season was longer during the early Holocene 11000 to 7000 BP (Williams, 1985). This has also been suggested to occur at this time in Sub Saharan tropical Africa (Sieffermann et al, 1988), tropical South America (Dickinson and Virji, 1987) and sub tropical Queensland. Sieffermann et al (1988) studied peatland development in Kalimantan. Their findings indicate that following the wetter, hotter and more humid period there was a strong decrease in rainfall over the past 5500 years. Williams (1985) states that much of Australia became drier with more erratic summer rainfall after 4500 BP.

It is evident that of the three environmental factors reviewed, long-term temperature changes are the most uncertain and difficult to predict. The influence of temperature changes on evapotranspiration from peat swamp forests may exert a stronger influence on the water balance and subsequent peat accumulation than does changes in rainfall.

At an ecosystem-scale of organization the moisture regime within peat profiles is mainly controlled by rainfall. At smaller spatiotemporal scales within peatlands two

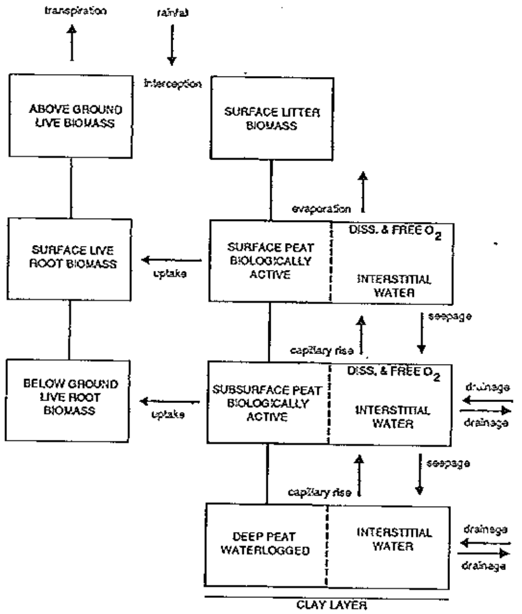

Fig. 4 Conceptual Model of Peat Water Distribution

main ecosystem components also influence the hydrological balance. One is the vertical profile of peat, the other is aboveground and belowground vegetation (Fig4).

PEAT PHYSICAL PROPERTIES

In undisturbed peatlands the upper zone of surface peat is between 5 to 30cm thick. It is comprised of recent vegetation litter at the surface and coarse, fibric peat in the 3 to 30 cm section. There is often a dense mat of fine roots between the layers of vegetation litter. The surface peat layer is highly porous as it receives continuous inputs of above ground litterfall. An active subsurface peat zone is located between 5 to 30 cm below the surface and is the zone of annual watertable fluctuation. It extends down to approximately 1 m in most undisturbed peatlands. Peat composition ranges widely from fibric to sapric in texture depending on the level of biological degradation. Roots frequently occur in this zone, growing downwards as the watertable drops and then dying back when water levels rise, thus continuously adding new organic matter to this zone. The bottom layer of subsurface peat is impervious to water seepage and a perched water table is formed. In peats thicker than 3 m this layer represents the largest accumulation of organic matter in the peat ecosystem.

A number of studies of different forest types included measurement of peat properties. Peat bulk densities[1] in unmanaged forests ranged from a minimum of 0.07 g/cm3 in the surface peat of low pole forest over deep peat to a maximum of 0.18 g/cm3 in the subsurface peat of tall mixed forest over medium depth peat. There were no significant differences in peat bulk densities between surface and subsurface peat under any forest type. There were significant differences though in surface peat bulk density between these areas and degraded mixed forest and agriculture areas. Surface peat in the agriculture area had the highest bulk densities ranging from 0.19 to 0.23 g/cm3, while the degraded mixed forest ranged between 0.16 and 0.22 g/cm3.

Differences in bulk density between areas and depths are attributed to a variety of factors including: the amount of compaction, botanical composition, mineral and moisture content, and the degree of decomposition (Andriesse, 1988). Considering the similarities of all study areas in moisture and vegetation inputs, the degree of decomposition is most likely to be responsible for the differences in bulk density. This has been confirmed in other peat studies. Driessen and Rochimah (1976) surveyed Indonesian peats and concluded that fibric, relatively undecomposed peat in pole forests had bulk densities between 0.11-0.08 g/cm3. More decomposed sapric[2] peats in mixed forest had values between 0.14-0.23 g/cm3.

Peat bulk densities are often extremely low in the subsurface waterlogged zone below approximately 1 m. This was recorded in the agriculture area where peat bulk density ranged between 0.050-0.067 g/cm3. The lowest bulk density found in the literature was 0.043 g/cm3 for deep peat in Jambi, Sumatra (Cameron, 1987). In contrast, Silvius et al (1984) found relatively high bulk densities of 0.16 g/cm3 at the 0 to 25 cm zone in 9 m deep peatlands in Jambi.

A peat survey was carried out 6 years after peat forest clearing and drainage for peat production in Kalimantan (Ministry of Mines and Energy, 1987). Results showed that upon development, peat structure had rapidly changed from the natural fibric and mesic textures to sapric. The bulk density of surface peat had increased to 0.22 g/cm3, while subsurface waterlogged peat remained at 0.16 g/cm3. A similar change appears to have occurred in the surface peat of both the DTMF and AGR areas. Results of this survey show that bulk densities throughout the entire profile in deep peatlands are naturally low. Higher bulk densities in surface layers are clearly caused by increased drainage in cleared and drained peat. The data suggest that high bulk densities in surface peat found in forested areas have resulted from a change in natural drainage patterns promoting greater decomposition rates. If true, the texture of surface peats can be used to predict the current state of the peat accumulation-decomposition balance of a particular peatland.

An analysis of particle size distribution helps to explain the differences in peat bulk densities between study areas and peat depths. The coarse fraction (20-0.05 mm) of peat in the surface layer of the low pole forest on deep peat was significantly higher than in any other depth or study areas, ranging between 56.1-79.7% of the total dry mass. The subsurface layer in this area was also significantly higher than the same layer in all other areas at 25.8-37.6%. A large proportion of this organic matter consists of live and dead roots of various sizes.

All of the pole forest areas contained significantly higher percentages of coarse matter in both surface and subsurface peat than either forested or degraded areas on medium peat with one exception. The subsurface peat layer in the agriculture area contained 13.7-22.9% coarse material. This is comparable to the texture of the subsurface layers in the deep peatland. The differences is because, upon forest clearing and subsequent cultivation, up to 50 cm of the surface peat has disappeared as a result of frequent burning and decomposition. The current surface layer was covered by 50 cm of peat prior to clearing in 1981. As most of the Agriculture area was not properly drained the watertable remained high, inhibiting decomposition of the subsurface zone.

If it can be assumed that the subsurface layers of all undrained medium and deep peatlands should be similar in texture and bulk density, then the low percentage of coarse particles measured in the subsurface layers of peat beneath the tall mixed (2.3-8.5%) and the degraded mixed (2.5-4.7%) forest suggest that increased decomposition has occurred in these layers. This is evident for the degraded forest which has been artificially drained by canals since 1982.

The tall mixed forest has not been artificially drained and was in fact flooded during the entire study period which took place in the wet season only. According to

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[1] Bulk density of dry samples: Dry Density in engineering terms

[2] See Appendix for definitions

people living near the forest the watertable in this undrained area does drop up to 1.5 m below the peat surface in some dry seasons, notably 1982-83 and 1987. In both years there were significant forest and peat fires burning in the same peat formation 20 km away. Although not artificially drained, the low amount of coarse organic matter in the subsurface layer suggests that the peat profile under the tall mixed forest is in a state of either net equilibrium or decomposition, but not accumulation.

Driessen et al (1976) performed fraction analysis on various Indonesian peats and found a similar pattern of increasing coarse fraction upon moving from mixed forest on medium peat to pole forest on deeper peat. However, his results of fraction analysis at different peat depths show an increase of coarse material with depth, and the greatest extreme found in mixed forest. He suggests that the subsurface peat is coarser than the surface layer because more of the fine fraction has been washed out in the saturated conditions.

The results show that in the deepest undrained peat study areas the surface layers always contain the larger percentage of coarse organic matter. In peatlands that have been cleared or drained (naturally or assisted) the surface peat has decomposed further resulting in a larger fine fraction as seen in the degraded mixed forest and agricultural study areas.

The range of total pore space was similar in all study areas in surface and subsurface peat and ranged between 78.6-95.1%. The pole forest areas had slightly higher percentages, but are not significantly different. The highest total pore space was found in the surface layer of the low pole forest on deep peat. These results are similar to the percentages and patterns determined by Driessen et al (1976). The particle density used for the calculations was 1.43 g/cm3. Driessen et al analyzed many types of Indonesian peats and found that particle densities ranged from 1.29-1.67 g/cm3. The factors leading to this range were unclear. It is suspected that the lower end of the range may better represent the particle density of fibric peats inder the pole forests. Much of this peat originated from tree roots. The roots of one particular species, Pandanus tectorius, are extremely common in peat. Ash (1987) measured the root density of Pandan at 0.4 g/cm3, while trunk density ranged from 0.12-0.4 g/cm3. The specific density of wood of many tree species found in the mixed peat forest on medium peat was much higher than Pandanus, ranging between 0.42-0.86 g/cm3 (Martawijaya et al, 1986).

Boelter (1974) measured total pore space in peats of different texture and determined that fibric peats contain up to 90% space by volume, while sapric peats contained around 80% total pore space. There classes apply well to the peats in the study areas which range from fibric in deep peat to hemic in texture on medium peat.

The division between capillary and noncapillary pore space was not determined during the study. However, it can be assumed that in the fibric deep peats a larger percentage of pores are noncapillary, large diameter pores (Pritchett, 1979). Probably of more importance than total pore space in peat is the distribution and connectedness of pore spaces (Kimmins, 1987).

In deep fibric peats on Padang Island much of the peat matter consisted of roots of different sizes and degrees of decomposition. In viewing soil pits and trenches it was observed that under forest vegetation there is a strong vertical pattern of root growth into the peat. Root growth appears to closely follow watertable fluctuations: extending rapidly downwards as the watertable drops and quickly dying back when the watertable rises for a lengthy period. The masses of dead and often hollow root sheaths create a distinct structure of vertically connected pore spaces. In the mesic and sapric surface layer of medium peatlands this vertically-oriented matrix of medium-sized roots was not observed as root growth and turnover was considerably less in these peats, perhaps due to increased mineralization and nutrient availablity in the once saturated peat.

With the available knowledge of the peat and the mechanisms of formation and deposition, it was concluded that road construction must not significantly modify the water table level in peat, or disrupt the drainage paths in the peat. This is stipulated in order to minimise fire risk, avoid affecting existing ecosystems, and avoid the possibility of regional settlement of the peat surface.

SOIL CONDITIONS

Field investigations of ground conditions were carried out, consisting of boreholes and Dutch cone testing. Laboratory testing was performed at the Institute of Road Engineering, Bandung, Indonesia. Additional special tests were carried out at the Engineering Services Section of the Research Institute for Water Research Development, and at the Mineral Technology Development Centre, both in Bandung.

The thickness of the peat identified from boreholes is shown on Fig. 5. Although mechanical Duch cone tests were also used these did not prove sufficiently sensitive to identify the boundary between the peat and the underlying very soft clay.

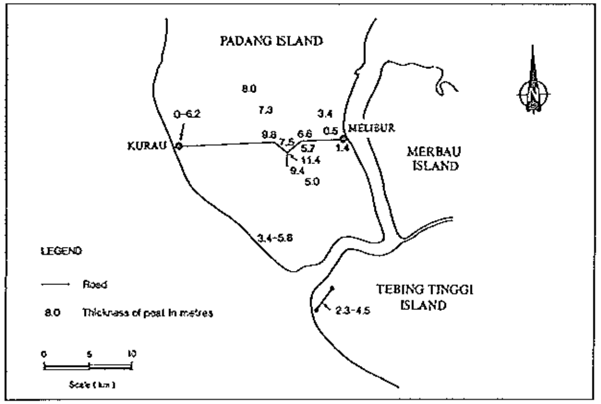

Fig. 5 Peat Thickness on Padang Island

Table 1 Profile of Peat in Pole Forest Area.

Depth		Recovery			o n Post Classn				
From	To	(m) [1]	(m) [2]	Description	H	B	F	R	W
0.0	0.5	0.20	0.17	Dark brown PEAT	4	2	3	1	1
0.5	1.0	0.26	0.21	Dark brown PEAT	5/6	2	3	1	1
1.0	1.5	0.39	0.28	Dark brown PEAT					
				disturbed 0 - 0.20	6	3	3	1	1
				0.20 - 0.28	4	2	3	1	1
1.5	2.0	0.29	0.25	Dark brown PEAT					
				disturbed 0 - 0.07					
				0.07-0.25	5	2/3	3	1	1
2.0	2.5	0.36	0.31	Dark brown PEAT					
				disturbed 0 - 0.19					
				0.19 - 0.31	4	2	3	1	2
2.5	3.0	0.35	0.33	Dark brown PEAT					
				disturbed 0 - 0.2					
				0.2 - 0.33	4	2	3	1	2
3.0	3.5	0.33	0.33	Dark brown PEAT					
				disturbed 0 - 0.19					
				0.19 - 0.33	4	2	3	2	1
3.5	4.0	0.37	0.30	Dark brown PEAT	4	2	3	2	1
4.0	4.5	0.23	0.20	Dark brown PEAT	3	2	3	2	1
4.5	5.0	0.26	0.24	Dark brown PEAT	3	2	2	3	0
5.0	5.5	0.26	0.20	Dark brown PEAT	3	2	2	3	0
5.5	6.0	0.35	0.24	Dark brown PEAT	3	2	2	3	0
6.0	6.5	0.35	0.24	Dark brown PEAT	3	2	2	3	0
				black at base	4	2	2	3	0
6.5	7.0	0.35	0.33	Dark brown PEAT	3	2	2	3	2
7.0	7.5	0.42	0.41	0 - 0.23 Dark brown PEAT	4	2	2	3	2
				0.23 - 0.41 Light grey very soft CLAY with some fragments of wood					
7.5	8.0	0.27		0 - 0.15 Brownish grey very soft CLAY with abundant brown root fragements					
				0.15 - 0.27 Light grey with dark grey mottling very soft CLAY					

Note
[1] sample length before extrusion
[2] sample length after extrusion

A detailed profile of the peat in the pole forest area is shown on Table 1. The higher von Post humification values in the upper part of the sample result from disturbance during the augering of the hole, and these parts of the sample were not logged in the lower parts. It is of interest that there is no apparent difference in the material with depth, down to the interface with the underlying very soft clay; this similarity with depth was also identified in the visual inspection of the samples.

Routine index tests, including moisture content, loss on ignition and bulk density did not differentiate the pole forest peat and the mixed forest peat. The results are shown on Fig. 6. Also a series of tests to measure volatile content and carbon contents produced no discernible differences.

The compressibility of the pole forest peat was assessed by back-analysis of the behaviour of existing roads, by field bearing tests and by laboratory oedometer tests. The results of two field bearing tests are shown on Fig. 7.

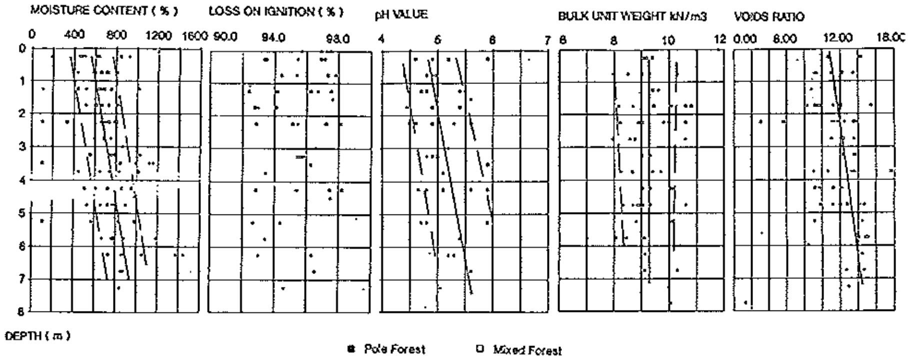

Fig. 6 Index Tests on Peat

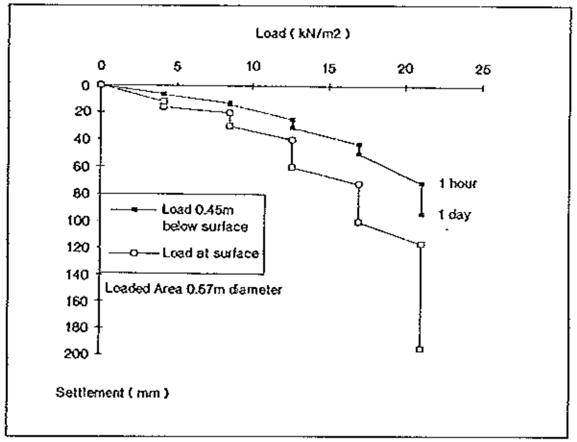

Fig. 7 Field Bearing Tests on Pole Forest Peat

Using the results from these bearing tests the road settlements derived were only some 0.5m, or about half the settlements measured on the failed roads constructed previously. This confirmed the substantial longer term creep settlement of the peat.

The permeability of peat is known to vary very widely, and is very difficult to measure. The need for adequate permeability data to assess the drainage control

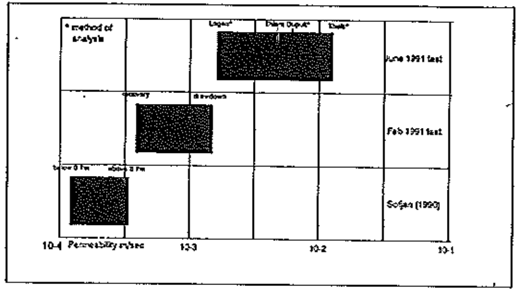

Fig. 8 Permeability of Pole Forest Peat.

Table 2 Permeability of Peat.

Peat description	Permeability m/sec	Ref
surface of bog acrotelm	$>10^{-1}$	Hobbs (1986)
base of slightly humified raised bog	3×10^{-5}	Hobbs (1986)
Russian fen acrotelm: near top near base	3×10^{-5} 6×10^{-7}	Hobbs (1986)
highly humified gelatinous Irish blanket peat	3×10^{-8} to 10^{-7}	Hobbs (1986)
highly humified blanket peat	6×10^{-10}	Hobbs (1986)
slightly humified fen peat	5×10^{-3}	Hobbs (1986)
sphagnum peat H8 to H10 H3	6×10^{-8} 10^{-5}	Hobbs (1986)
Sedge peat H3 to H5	10^{-5}	Hobbs (1986)
Brushwood peat H3 to H6	10^{-5}	Hobbs (1986)
fibrous acidic Malaysian peat	2×10^{-5} to 6×10^{-8}	Toh et al, 1990

measures required, and the possible regional effects of local drainage measures, resulted in a number of field trials to obtain permeability values. The results are shown on Fig. 8, and compared with published data for peat in Table 2.

Underlying the peat is a recent clay; this is soft, becoming firm with depth, organic and sometimes peaty in the upper part. From 35m below sea level sand lenses or layers have been identified within the clay; there is considerable variation in level and thickness of these layers even over short distances.

THE DESIGN ADOPTED DRAINAGE CONTROL MEASURES

Drainage measures are often considered to be detrimental, and even unproductive in peat, as they can cause extensive settlement. Lowering of the water table may be expected to cause settlement by three mechanisms:

a) increase in effective stress, causing a rapid settlement in permeable peat
b) drying shrinkage, which causes irreversible changes in the peat
c) allowing aerobic conditions, resulting in an increased rate of decomposition.

If ditch water levels are controlled so that groundwater levels are not lowered below natural seasonal minimums, further settlement by mechanism a) should not occur; further drying is unlikely, so the only effect of drainage measures is then to provide an extended period of the year for decomposition. The evidence is that decomposition rates are very slow in the pole forest peat, and thus there should not be a major concern. It was therefore concluded that drainage measures sufficent to control flooding should be adopted; field monitoring data supported ths conclusion; peat surface variations over three years of seasonal water table fluctuation were very small as shown on Fig. 3.

The cutting of ditches alongside the road had previously been routine; field monitoring indicated that a ditch cut close to the road increases settlement by reducing the ability of the peat to act as a mat. Therefore it was concluded that, where practicable, ditches should be located at least 15m from the edge of the road.

ROAD CONSTRUCTION

Road construction had consisted of a nominal 50cm of imported crusher-run granite stone pavement generally, placed over layers of corduroy with a geotextile separator. In mixed forest peat areas very limited corduroy had been used, whilst in the pole forest up to four layers had been adopted.

In the mixed forest peat areas the roads had performed satisfactorily; in the pole forest peat areas however settlements of roads and hardstands had been substantial, up to 1.2m having been measured and larger amounts reported to have occurred. The consequence of the settlements is that the roads were at, or below, general ground level and were flooded and impassable during the rainy season; extensive damage was caused to the road pavement when the flooded roads were trafficked.

The roads are required to carry a 10 tonne axle load, with some 5000 axles, the majority during construction.

Road construction must not significantly modify the water table level in peat, or disrupt the drainage paths in the peat. This is stipulated in order to minimise fire risk, avoid affecting existing ecosystems, and avoid the possibility of regional settlement of the peat surface. These constraints form part of a wider forest management system aimed at minimising disturbance (Brady & Kosasih, 1991). The fire risk is of particular importance since studies and trials have shown that regeneration of the pole forest after clearing is feasible, but after burning of the surface, as has been carried out in attempts at agricultural development, the pole forest trees are unable to regerminate.

The variation in performance of previously constructed roads relates closely to the type of peat on which they are constructed. Roads near the coast are on mangrove or peatswamp deposits and have performed well when constructed from two layers or less of corduroy. Roads constructed on pole forest peat have performed badly however many layers of corduroy are used.

Failure of existing roads has been caused by trafficking during flooding. Therefore the requirement for a successful road is that it remains above flood level.

The environmental design criteria would not allow for deep drainage and flood relief systems. If no special drainage measures are adopted to control flooding then it is estimated that the road surface should remain a minimum of 0.5m above ground level during its life.

A road constructed from corduroy and stone has been shown not to be capable, in general, of remaining 0.5m above the surrounding ground. A timber piled raft with a geogrid reinforced stone pavement has been designed and confirmed by field trials to perform satisfactorily. Details of the design are shown on Fig. 9; details of the pile loading trials and design have been described elsewhere (Barry et al, 1992). Approximate costs for this scheme are US$350,000 per kilometre.

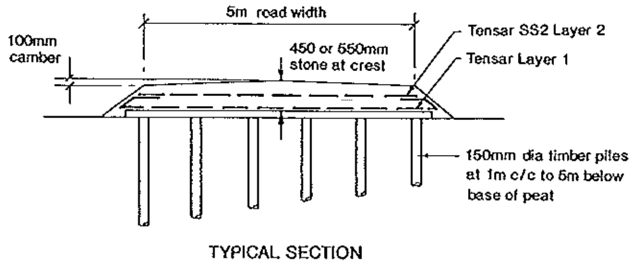

Fig. 9 Piled Embankment Layout

The raft and pile design caters only for dead loads; short- term, transient, live loads should be able to be accepted since the structure will have a higher strength for transient loads. However parked trucks, for example, would need to be placed in specially designated parking areas suitably designed for the additional load.

The suitability of the design was tested by construction of a number of trial sections, including a length constructed with no piling. A comparison of the section subsequently adopted for use, and the unpiled section, is shown on Fig.10.

As an alternative to piling, the construction of a higher embankment using low-density fill materials was investigated. Preliminary studies indicate that polystyrene blocks and lightweight clay aggregate offer possibilities; however the setting up of a suitable source of these materials would only be a potentially economic alternative to piled embankments if there is a substantial additional amount of new road to be constructed.

CONCLUSIONS

Careful environmental investigation and identification of environmental constraints allowed the construction of roads through environmentally sensitive areas with minimum effects on the environment. This approach is likely to become essential for the provision of access into underdeveloped areas of the world.

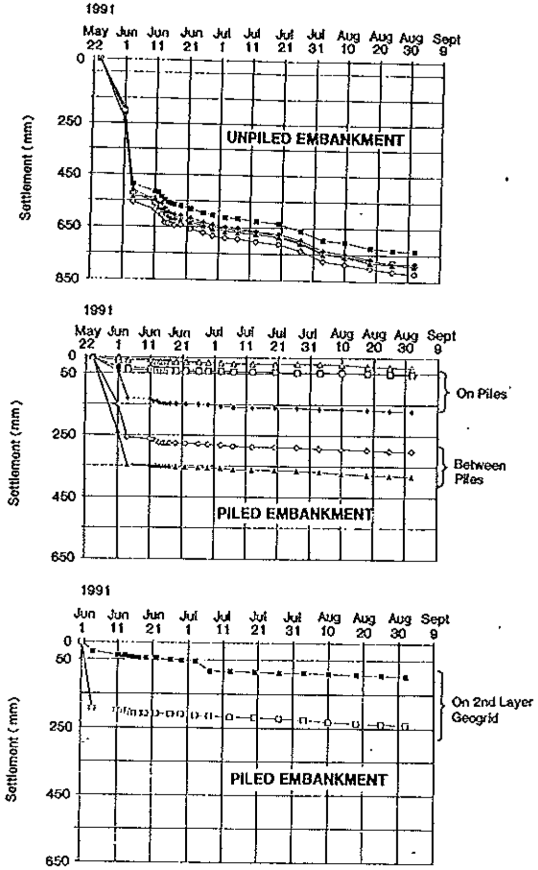

Fig. 10 Settlements of Road Trial Sections

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APPENDIX

The terms used for the descriptions of peat are:

mesic	undecayed unsaturated zone		
ombrogenous	formed with nutrient derived solely from rainwater, and therefore poor in minerals		
sapric	decayed and water saturated zone		
von Post Classification	H	Humification	(1: no decomposition to: 10: complete decomposition)
	B	Water Content	(1: dry to 5: very high)
	F	Fine fibres	(0: nil to 3: high)
	R	Coarse fibres	(ditto)
	W	Wood/shrub remains	(ditto)

for a comprehensive description see Hobbs (1986).