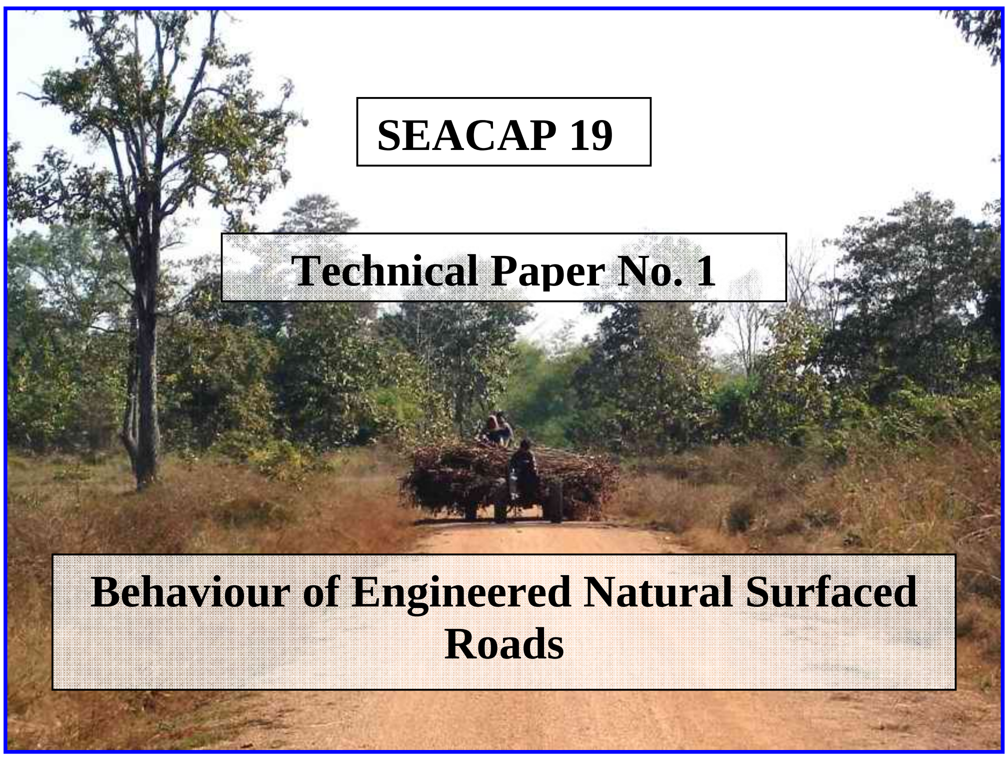
ROYAL GOVERNMENT OF CAMBODIA

SOUTH EAST ASIA COMMUNITY ACCESS PROGRAMME

DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS



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SOUTH EAST ASIA COMMUNITY ACCESS PROGRAMME

DEVELOPMENT OF LOCAL RESOURCE BASED STANDARDS

SEACAP 19 Technical Paper No 2

Behaviour of Engineered Natural Surfaced Roads

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CONTENTS

ABBREVIATIONS AND TERMINOLOGY

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic (sum of both directions)
CBR	California Bearing Ratio
ENS	Engineered Natural Surface
ENSR	Engineered Natural Surfaced Roads
GC	Grading Coefficient
GVW	Gross Vehicle Weight
HDM III	Highway Design and Maintenance Standards Model version III
HDM 4	Highway Development Model version 4
Ip	Plasticity Index
km	kilometre
KN	Kilo Newtons
LS	Linear Shrinkage
LVRR	Low Volume Rural Roads
m	metres
mm	millimetres
MMP	Mean Monthly Precipitation
MN	Mega Newtons
Pavement	Roads comprising only unmodified in situ material are often called unpaved roads because no additional material is added. However, in the context of an ENSR (and this review) the term 'pavement' is used to describe the 'engineered' layers of the road in the normal way.
P##	Passing sieve size ##
PP	Plasticity Product
PI	Plasticity Index
PSD	Particle Size Distribution
psi	pounds per square inch
SEA	South East Asia
SEACAP	South East Asia Community Access Programme
ToR	Terms of Reference
US	United States
UNDP	United Nations Development Programme
vpd	vehicles per day

SEACAP 19: Technical Paper No. 2

Behaviour of engineered natural surfaced roads

1 SCOPE

The general subject of Engineered Natural Surfaced Roads (ENRs) and their provision is very wide, covering planning, design, construction, management, water crossing structures, community involvement, economics, maintenance, management and so on. The topic as defined in the Task ToR can also encompasses a wide range of natural materials, from in situ rock to weak soils.

This review however, is primarily concerned with the basic behaviour of the 'pavement' itself, defined in this context as the road surfacing and the layers of natural insitu materials in the zone below the surface. The review also concentrates on the use of "earth" materials; or those materials whose quality could be categorised as below that which is normally acceptable for use as an unsealed gravel wearing course. Within this definition the overall objective of Task 2 in the SEACAP 19 programme is to define the conditions under which an earth surface is a reasonable choice of road surface type to use. Thus it is assumed that along the route water crossings are adequate for all-year access and that, provided the earth surface is sufficiently durable and socially acceptable, then such a solution can be viable. The purpose of this review is to identify all the principal factors on which the performance of an earth road depends so that a field survey of actual performance in Cambodia can be designed to record values of the important variables and to help define critical limits.

No truly low-cost surfacing can last for very long without maintenance and so knowledge of the type and amount of maintenance that is needed is an important part of the process of selecting a road surfacing. Maintenance is therefore an important issue but it is not considered in detail in this report. It will be discussed after the field surveys have been completed; only then will the achievable types and levels of maintenance be known.

2 INTRODUCTION

A road surface must withstand the loads imposed by traffic and the effects of climate, principally rain (precipitation) but possibly including the effects of the level of the water table and flooding. The ability of a soil to support traffic can be related to the shear strength of the soil and this, in turn, is traditionally related by road engineers to the California Bearing Ratio (CBR) of the soil. Naturally this depends on the soil itself, its level of compaction and the moisture conditions. Since the moisture conditions change with precipitation throughout the year, and because many soils will not be strong enough to support even moderate levels of traffic when they are too wet, it is necessary to define the level of access that we require of a road fairly carefully. In practice it has been quite difficult to define the 'passability' of a road in a clear and unambiguous way. Table 2.1 provides an accepted set of characteristics which define basic access. This is the highest level of service likely to be achieved by means of an ENSR.

The choice of *standard vehicle* (see Table 2.1) depends on the use of the road and is normally the common vehicle that makes the most demands on the road in terms of engineering standard. For example, a standard vehicle for a road carrying considerable agricultural produce might be a 3-tonne truck, but a pick up or even a motor tricycle might be the standard vehicle for a road where heavier vehicles are rare.

The *standard speed* is not used to define the speed that the standard vehicle can travel along the road but the speed at which the standard vehicle travels through the critical sites along the road. For most ENSRs there will be places where an ENS is not good enough and therefore localised improvements will be required (see paragraph 3.4 below). These are often first identified where the standard speed becomes too low.

Table 2.1 Definitions of basic access service levels for ENSRs

<table>
<tr><th></th><th></th><th>Criteria</th><th>Interpretation</th></tr>
<tr><td rowspan="6">A road provides basic access if all of these criteria are met.</td><td>A</td><td>The standard vehicle can pass all year round except for a period of up to 24 hours following rain</td><td>This is primarily a means of defining the standards of the water crossings and the time required for excess water to dissipate but there is also an important effect of rain on many fine grained soils that cause them to be too slippery to maintain sufficient traction for vehicles</td></tr>
<tr><td>B</td><td>The standard vehicle does not need to travel slower than the standard speed</td><td>As most road surfaces deteriorate, their unevenness (or roughness) increases until eventually it become so high that vehicle speeds are seriously affected. However, it is likely that criteria C, D and E will be violated before this happens. Some soils, primarily sandy soils, lack cohesion and the soil itself can impede vehicle movement.</td></tr>
<tr><td>C</td><td>The standard vehicle can pass safely without risk of injury to the driver, passengers and other road users</td><td>This is both a ‘roughness’ criterion and a geometric alignment criterion. The road must provide space and sight distances commensurate with safety as well as an acceptable ride quality</td></tr>
<tr><td>D</td><td>The standard vehicle can pass without being damaged and without damaging its cargo beyond normal wear and tear</td><td>This is primarily a ‘roughness’ criterion</td></tr>
<tr><td>E</td><td>The standard vehicle can pass without damaging the road beyond normal wear and tear, even when it is raining</td><td>This is essentially a soil strength issue but is also closely linked to permeability (the amount of water that can soak into the surface in a given period) and therefore the depth of soil that is seriously weakened during rain</td></tr>
<tr><td>F</td><td>It is unlikely that the road will deteriorate at a rate in excess of a predefined standard</td><td>Overall deterioration is manifested by deterioration of ride quality (roughness) but includes effects that arise from different causes. Thus rut development depends on traffic, erosion depends on rainfall, but both contribute to increases in roughness.</td></tr>
</table>

From TRL (2006) *Spot Improvement Manual for Basic Access*

3 GENERAL BEHAVIOUR OF ENGINEERED NATURAL SURFACES

An ENS will always deteriorate with time as well as with traffic. Under even moderate climatic conditions and easy terrain, some soil types will deteriorate too quickly for an ENS to be a viable surface option. The properties of the local soil and the local environment are fundamental and, for example, it is anticipated that few soils will make a viable ENS if the longitudinal gradient is too high. However, it is impossible to be prescriptive because the best choice of surfacing will depend on the whole life costs of all the options and this, in turn, will depend on the alternatives that are available and a range of influencing factors at each road location.

The deterioration of ENSRs is governed by the combined actions of traffic and the environment and, most of the time, it is at the surface itself that deterioration occurs. However, although by definition a length of road comprises only one type of material, the surfacing may be relatively dry and strong for much of the time whereas the underlying material may be wetter, less compacted, and consequently weaker. If this weaker material is too close to the surface it may be at risk of failure. For example, this can occur if the embankment height in low lying areas is inadequate. Under these circumstances it may sometimes be necessary to consider the pavement as a layered structure in much the same way as is done for normal multilayered pavements and to consider likely failures at depth, but under most circumstances this will not be necessary.

The surface of an ENSR is usually permeable although, in some cases, the permeability may be very low; thus material properties, rainfall, and surface drainage influence the behaviour of the surfacing itself. On the other hand, surface water run-off and side drainage usually affect the moisture penetration into the underlying layer (roadbed) and thus its bearing capacity.

There are three principal mechanisms of deterioration namely:

(i) Deformation of the surface (and possibly the roadbed material) under the stresses induced by traffic loading.

(ii) Wear and abrasion of the surface material under traffic.

(iii) Erosion of the surface by traffic, water and wind.

The modes of deterioration in dry weather and in wet weather will therefore be different.

3.1 Dry weather deterioration

Under dry weather conditions, the most prominent deterioration mechanisms are:

(i) Wear and abrasion of the surface material (thereby generating loose material and promoting ruts).

(ii) Loss of the surfacing material as dust and through ‘whip off’ by traffic.

(iii) Movement of loose material under traffic action to form corrugations.

These mechanisms result in roughness and material loss, with the rates of deterioration being primarily a function of the properties of the surfacing material and traffic.

3.2 Wet weather deterioration of adequate pavements

Under wet weather conditions the shear strength of the materials determines the pattern of deterioration. When the shear strengths of the surfacing and roadbed materials are adequate for the stresses induced by traffic, deterioration occurs only at the surface. The major modes of deterioration under these conditions are:

(i) Environmental and traffic influences on surface erosion.

(ii) Wear and abrasion of the surface by traffic causing rutting and loss of the surfacing material.

(iii) Formation of potholes under traffic action. Free water on the surface accumulates in any depressions. The passage of a vehicle tyre stirs up the water causing fine material to pass into suspension. Water, with the suspended fine material, is also forced out of the depression. Under the action of many wheel passages and sufficient water, this is a rapidly accelerating phenomenon.

3.3 Wet weather deterioration with weak material

When the surfacing layer has inadequate shear strength to sustain the stresses applied by traffic loadings, shear failure and deformation occur. The road surface will be soft and even slushy under wet conditions so that, while it may be possible for a few light vehicles to pass, the road will become impassable after a relatively small number of vehicle passages. Traditionally, index tests such as the California Bearing Ratio (CBR) have been used in road engineering to identify materials that resist shear failures, but material properties such as plasticity and fineness, also influence the behaviour under these conditions. More fundamentally, the mineralogy and structure of a material are also likely to have an influence in some soil groups; this is discussed in Section 4.3 below. There are some materials, principally fine-grained with very low wet shear strength, for which loss of wheel traction is a primary cause of impassability rather than pavement deterioration. This issue is discussed further in Section 5.8.

3.4 Local environmentally optimised design

The ideal ENS will therefore have the following characteristics. It will be:

- strong - to support traffic,
- impermeable - to shed water quickly,
- erosion resistant (by having a suitable particle size distribution)
- smooth - so that the ride quality will be good,
- durable - so that these qualities last a long time,
- easy to maintain.

A little thought will show that many of these characteristics are conflicting. For example, a coarse soil with a relatively large maximum particle size may be strong and will resist erosion but the ride quality may be poor and carrying out maintenance may be relatively difficult. It is useful to discuss all the conflicting requirements of an ENS to help define the kind of soils that are likely to be acceptable.

For the conditions of SEA it is thought that some soils will have an acceptable mixture of properties, but this is not guaranteed. Furthermore it is not expected that such a soil will form a suitable surface for the complete length of a road. Some sections, for example, on gradients or water crossing points, will need more robust surfacings. This is the principle of ‘spot’ design whereby the optimum choice of design is based not on the properties of the whole road but on an assessment of the properties and individual design of separate but uniform sections within it.

4 BEARING CAPACITY

4.1 Strength of soil

All soils, with the exception of those in the most arid regions of the world, will become wet at some time during the year. In SEA this will happen throughout a sizeable proportion of the year, thus the behaviour of a soil in a wet or a saturated state is an important factor for determining the likely service level of the road.

For the armed forces the traffic carrying capacity of a soil is critical. An army needs to know whether a soil will carry vehicles for long enough for all of its equipment to pass through a critical point or whether a strengthened road needs to be built. If this is not known, a battle might be lost. Therefore the US Army carried out a great deal of research into this problem and much of the knowledge concerning the relationship between soil strength, wheel loads, tyre pressures, and traffic carrying potential of soils derives from this research. Unfortunately most of it was carried out a relatively long time ago (from 1947 to circa 1975) and it is therefore often overlooked. A short paper by Ahlvin and Hammitt (1976) has summarised much of this work and is the basis for the following calculations (Figure 4.1) showing the relationships between soil strength, tyre pressure, axle load and vehicle passages for a failure rut depth of 75 mm. Although this rut depth is not excessive, surface run off is severely impeded and deterioration progresses rapidly hereafter if rain occurs.

Figure 4.1 shows the relative small effect of axle or wheel load compared with tyre pressure and the very sharp rise in traffic carrying capacity as soil CBR increases. To put the data into perspective, if we assume that in Cambodia the rainy season lasts for 5 months then the number of wet days per year will be about 150. It is only in the wet season that the soil is weak and we assume that in the dry season bearing capacity is not a problem. Thus 25,000 passages represents the equivalent of 167 vehicles per day for 1 year, 83 vpd for 2 years, 56 vpd for 3 years, 42 vpd for 4 years , 33 vpd for 5 years and so on. These are realistic or even conservative estimates of traffic considering that the standard vehicle being considered has an axle load of 80 KN and a tyre pressure of 75 psi (0.52 MN/m^2) - it is typically a 10-tonne truck. In addition, the road will also carry many more lighter vehicles.

Figure 4.1 shows a critical CBR of about 13% for this standard vehicle; at this point the traffic carrying potential of the road is increasing very quickly as CBR increases. The importance of tyre pressure rather than wheel load is illustrated by the right hand curve in the Figure. If the tyre pressure is increased to 100 psi (0.69 MN/m^2), then the critical CBR increases to about 18%. This is a considerable increase. In terms of shear strength it is approximately an increase from 400 to 550 KPa, equivalent in soil mechanics terms to a hard clayey soil.

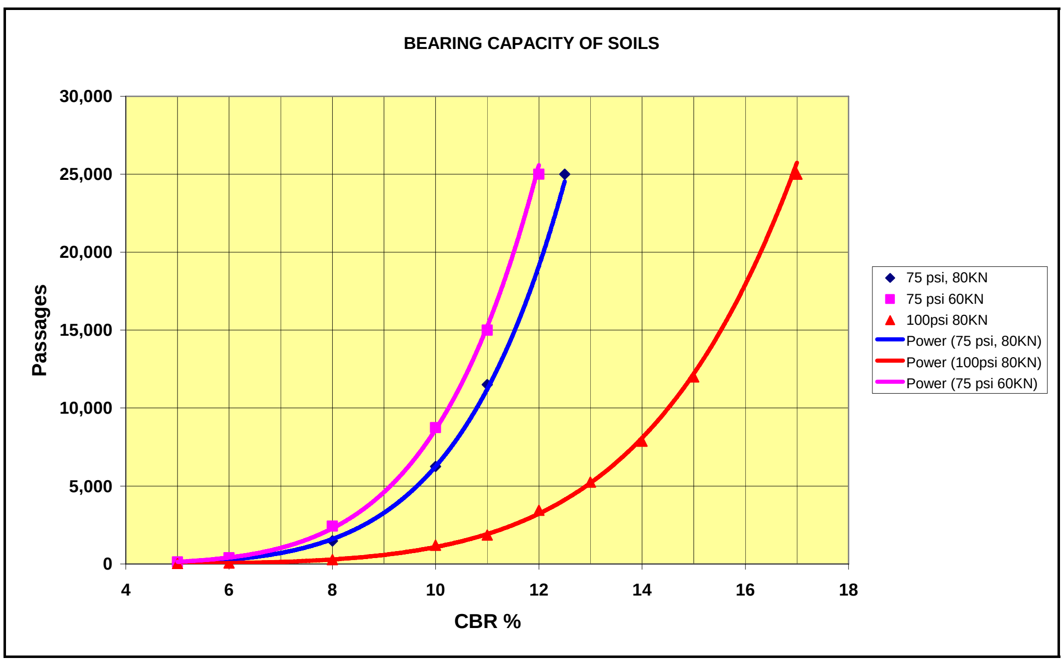


Figure 4.1 Bearing capacity of soils (from Ahlvin and Hammitt, 1976)

It should be noted that roads with surfacings of these strengths will be capable of carrying far more vehicles with lower tyre pressures, many hundreds per day in fact. However, non-pneumatic or solid wheels may impose higher stresses because of their small contact area. In some places this is a potentially serious problem.

More recent empirical studies by Visser (1981) also showed that the soaked CBR of the surfacing material was a reliable indicator of passability. The criterion proposed by Visser for ensuring that a road remains passable during a wet season (providing that there is no flooding) is:

$$SFCBR > 8.25 + 3.75 \log_{10}(ADT)$$

where,

SFCBR = soaked CBR at standard AASHTO compaction (%)

ADT = average daily traffic in both directions, in vehicles per day.

Thus if SFCBR exceeds this value, the road should remain passable all through a rainy season. Visser's experiments took place on normal roads under typical traffic conditions and so the effects of tyre pressure and wheel loads could not be measured separately. The average daily traffic on the test roads contained differing numbers of trucks and a variety of axle loads and tyre pressures. However, if we assume that 10% of the vehicles were trucks and that they were almost certainly overloaded, we can draw a rather approximate comparison with the US Army data. With these assumptions, an ADT of 400 is equivalent to about 40 trucks and the Visser criterion (equation above) suggests that SFCBR must exceed about 18%. This is similar to the criterion derived above from the US Army data for trucks with a degree of overload (e.g. tyre pressures of 100 psi). This agreement is encouraging.

The degree of saturation that occurs during a typical rainy day in the wet season depends on the permeability of the soil, the camber or slope of the road and the opportunities for evaporation and drying. Low permeability is associated with fine-grained soils which tend to have higher plasticity and to be relatively weak when wet so the ideal soil will be a compromise between low permeability (low wet strength) and high wet strength (high permeability). It is worth noting as an example that a good quality, true laterite gravel will generally meet this compromise objective.

There is one interesting aspect of this trade-off. Many relatively impermeable soils are extremely slippery when wet. Thus, although they are very weak when wet, the weak layer is very thin (because the permeability is low) and the slipperiness ensures that traffic cannot actually travel on them until they have dried sufficiently. They are therefore 'self-protecting' and generally have good performance in terms of a low deterioration rate. Note that the criteria discussed above do not explicitly take this into account.

4.2 Other soil characteristics influencing bearing capacity

Studies of the performance of unpaved roads have often focussed on the effects of particle size distribution (PSD) and plasticity rather than the basic strength of the soil. This is because the strength depends on compaction level and current moisture content, both of which are always changing and hence difficult to measure or quantify adequately, whereas it was thought that particle size distribution and plasticity were relative constants. Thus, in principle, models could be developed relating the performance of a variety of surfacings, each with different values of these and other 'constant' parameters such as gradient and width, to the independent variables of traffic and rainfall, variables that could be measured relatively easily. Such models are capable of taking into account the deterioration caused by environment as well as traffic because, for example, erosion effects will also depend on PSD, plasticity, rainfall, road geometry and so on. Such models are used in road investment and management tools such as HDM 4 but those for unpaved roads are not well developed compared with the models for paved roads. They are discussed in more detail below.

Clearly soil strength is also highly correlated with PSD and plasticity but it is difficult to compare the two approaches unless ALL the required data have been collected for the test sites so that strength can also be related to the other variables. To our knowledge this has not been done for roads in environments similar to those in SE Asia.

4.3 Tropical Soils

One significant issue with regard to understanding the behaviour of soils in SEA is that they are likely to have been formed by tropical weathering processes (where chemical alteration is dominant) as opposed to the more traditional soils from European and similar climates where physical weathering is more dominant in soil formation. In the field of geotechnics it is now recognised that many of the traditional empirical relationships derived for classifying soil may not hold true for tropical soils and that great care has to be taken in the use of traditional soil testing and interpretation (GSL, 2000). The influence of mineralogy together with soil structure and its destruction have a more widespread influence on the behaviour of tropical soils than on that of temperate soils. With respect to the more robust gravelly materials normally associated with pavement construction, this contrast in behaviour is not generally relevant; however, weaker, non-standard soils used in ENSRs may well be outside the envelope of established pavement engineering assumptions on material behaviour.

The above concept can be briefly illustrated by two examples. Firstly, there is an assumed relationship between Linear Shrinkage (LS) and Plasticity (Ip) , where Ip = 2.13 x LS. Table 4.1 shows variations in this relation for tropical soils of different mineralogy along a single road alignment. Secondly, the influence of fabric and the effect of total destructuring and wetting up is shown in Figure 4.2, where moisture content is plotted against shear strength for both slurried and normally remoulded materials.

Table 4.1 Plasticity-Linear Shrinkage for Some Tropical Soils (West Java Toll Road)

Material	Minerology	Average Ip	Average Ip/LS	No of samples
Tropically weathered silty mudstone	Kaolinite; Smectite	44	3.06	13
Tropically weathered mudstone	Smectite dominant	59	5.18	26
Tropically weathered volcanic ash	Kaolinite-Halloysite	36	1.59	120

Source: (Cook, 1997)

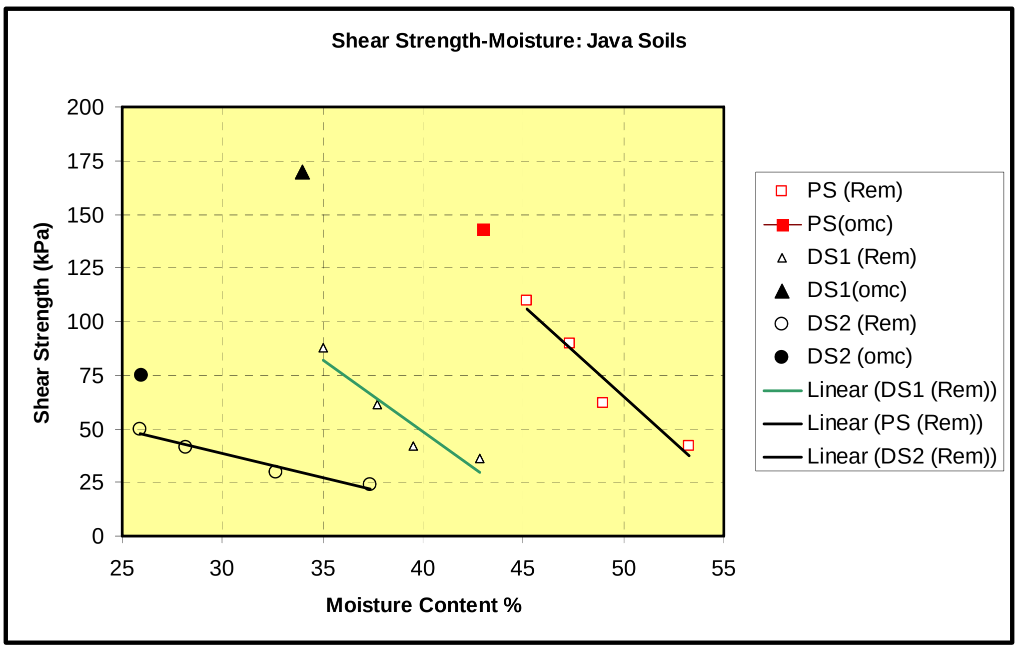


Figure 4.2 Effect of moisture content on shear strength (Cook, 1997)

D: Poorly structured volcanic soil S1: Distinctly structured volcanic soil

S1: Distinctly structured residual mudrock soil

(Rem): Completely destructured condition (omc) Remoulded only by compaction

The distinctly structured soils (DS1 and DS2) indicate a change in strength behaviour between normally remoulded and totally destructured conditions, whilst the poorly structured soil (PS) does not.

The concept of varying levels of disturbance behaviour is important when considering sample test condition (i.e. normally remoulded) as against total destructuring as is likely to happen under wheel-spin conditions on an earth road. Some structured soils for example, even when normally remoulded, retain a residual fabric which, on destructuring, can release previously held water and further weaken the material; hence the commonly observed slurrying of material under the spinning wheels of a stuck vehicle; as modelled by soils DS1 and DS2 in Figure 4.2 .

In summary, care needs to taken in using standard behaviour assumptions based on "traditional" soils when dealing with tropically weathered soils such as, for example, latosols (lateritic red clays) andosols or vertisols. The proposed ENSRs research should include some cross-checking of behaviour patterns and relationships such shear strength versus CBR and shear strength versus disturbance and moisture content.

5 DETERIORATION TRENDS

5.1 General trends with PSD and plasticity

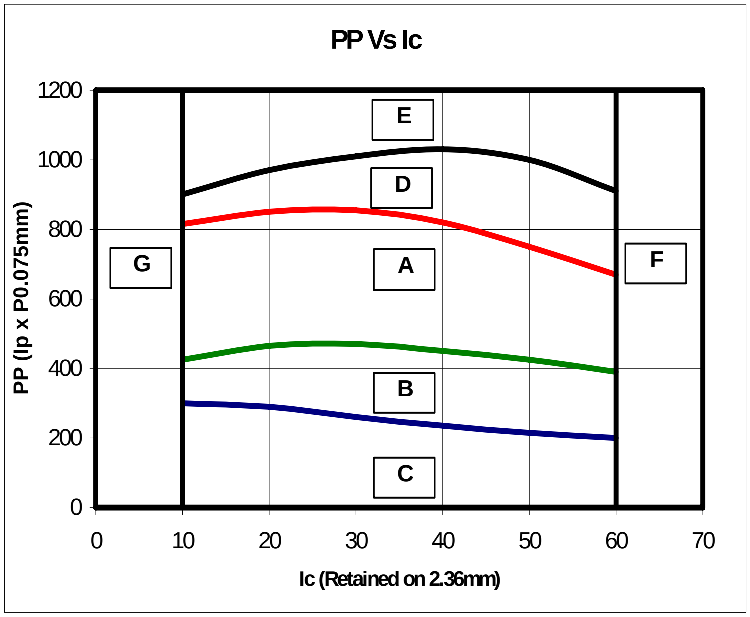
The chart shown as Figure 5.1 illustrates the general trends that occur as the PSD and plasticity characteristics of soils are changed. The chart was developed primarily for gravels but the area on the left of the diagram covers the finer-grained materials that include most natural soils. It can be seen that there is considerable scope for such soils to fall into categories A and B, where good performance as road surfaces is expected, although many will also fall into the unsatisfactory categories, particularly category G where particles of sand size and above are largely absent and category C, which comprises silty sands lacking cohesion.

A similar chart based on Shrinkage Product and Grading Coefficient has been developed from extensive research in southern Africa. This chart is shown in Figure 5.2 P Two versions of the chart exist depending on whether the test methods used are the British Standards or the American ASTM standards (P Paige-Greene, 2007); the chart appropriate to the British Standards is shown. Shrinkage Product is defined as the product of Linear Shrinkage and the percentage of material passing the 0.425 mm sieve (i.e. the fraction of material used for the test itself). The Grading Coefficient is defined as follows,

$$GC = P4.75*(P26.5 - P2.0)/100$$

where P4.75, P26.5, P2.0 are the percentages passing the 4.75, 26.5 and 2.0 mm sieves respectively. Sometimes the 5.0 mm and 28 mm sieves are used instead of the 4.75 and 26.5 mm sieves.

Comparison of the predictions of the two charts for a range of typical materials shows good general agreement, as one might expect, but one significant difference is that the Paige-Greene chart (Figure 5.2 P) gives more emphasis on plasticity and indicates poorer performance for materials with high plasticity than indicated in Figure 5.1 . In other words some materials rated as *'good'* in Figure 5.1 are sometimes rated as *'(too) slippery when wet'* in Figure 5.2 P. Also, some materials rated as *'good'* in Figure 5.1 fall just inside area B in Figure 5.2 Pand are therefore rated as *'erodable'*.



A: Good performance under wet and dry conditions
B Good performance under wet conditions; corrugates in dry conditions
C Lacks cohesion: rapid deterioration with trafiic
D Good in dry conditions; slippery in wet; potholes/erosion
E Poor in both wet and dry conditions
F Too coarse: erodes badly; difficult to maintain
G Too fine; trafficability problems in wet and very dusty when dry

Figure 5.1 Performance trends with PSD and Plasticity Product

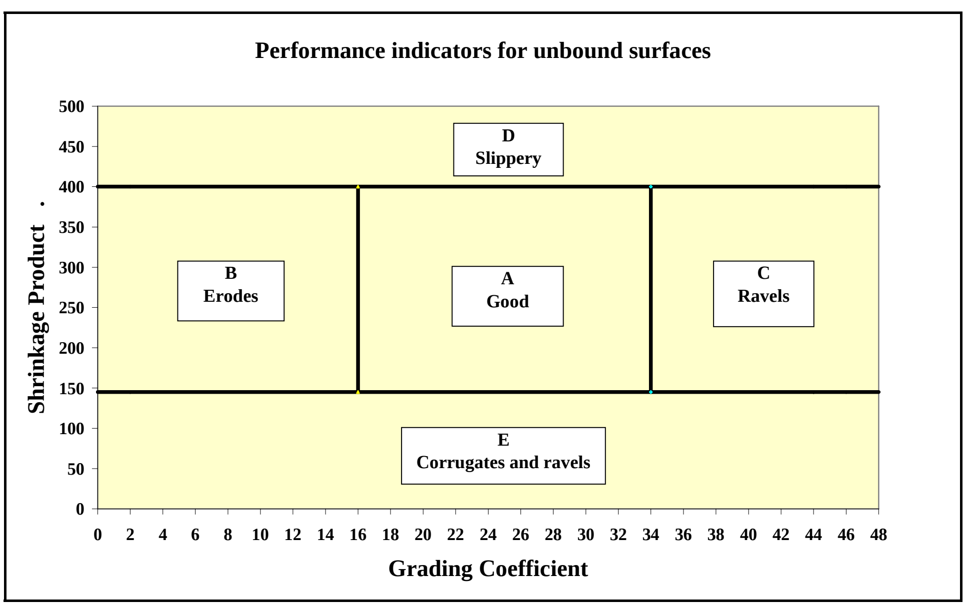


Figure 5.2 Performance trends with Shrinkage Product and Grading Coefficient (Source: P Paige-Greene, 2007)

These two charts are based on research in drier environments and on largely different (non-tropical) materials to those found in SEA, therefore exact agreement with performance trends observed in Cambodia is not expected. Therefore, although the general trends will be similar, and taking into account the fact that the boundary lines between the different regions of the charts are based on considerable engineering judgement, the differences may be sufficient for new charts specific to SEA to be devised.

5.2 Erosion

As well as the traffic effects discussed in Chapter 4, the other major cause of surface deterioration is erosion. Erosion has been studied extensively for agricultural purposes, where soils are loose (uncompacted). Much less data are available concerning engineered surfaces although it is reasonable to expect that the same variables are involved. Lack of cohesion is associated with an absence or deficiency in the clay fraction. In a gravel material with plenty of medium and coarse gravel sizes present, lack of clay is not so critical because mechanical interlock will help prevent erosion. In fine-grained material, lack of clay means lack of cohesion. Thus materials that are predominantly silt and sand-sized are extremely prone to erosion (category C in Figure 5.1).

The extensive research on the erosion of soils in agricultural situations has produced complex and comprehensive models (e.g. the Universal Soil Loss Equation or USLE and the Water Erosion Prediction Project (WEPP) in the USA) but these are not considered applicable for use on ENS roads; they tend to predict high levels of erosion.

5.3 Predicting deterioration or performance

Although the performances of unpaved roads have been studied extensively, most of the studies have concentrated on gravel-surfaced roads and have tended to focus on the behaviour of roads carrying relatively high levels of traffic. The reason for this is that large economic penalties occur, in whole life cost terms, if high levels of traffic travel on rough surfaces. This is because the cost of operating vehicles on such roads can rise rapidly as roughness increases. Hence it is important to identify the conditions that justify upgrading gravel roads to a sealed surface standard and to determine optimum maintenance policies. Thus tools such as the HDM III and HDM 4 computer models have been developed to help engineers, economists and planners to make these investment decisions. The best of these models include equations for predicting the performance of unpaved roads based on all the factors that come into play. These include traffic factors, environment factors and material properties as discussed above.

5.4 Roughness

The model form adopted in HDM constrains the roughness to a high upper limit, or maximum roughness (RI_{max}), by a convex function in which the rate of increase in roughness decreases linearly with roughness to zero at RI_{max}. From the results of the Brazil UNDP study, which led to HDM III (Paterson, 1987), the maximum roughness was found to be a function of material properties and road geometry, and the rate of roughness progression to be a function of the roughness, maximum roughness, time, light and heavy vehicle passes and material properties. The HDM-III roughness progression relationship is given by:

$$RI_{TG2} = RI_{max} - b\,[RI_{max} - RI_{TG1}]$$

where,

$$RI_{max} = \max\{[21.5 - 32.4(0.5 - MDR)^2 + 0.017(HC) - 0.764(RF)(MMP/1000)],\ 11.5\}$$

b	=	$\exp[c(TG_2 - TG_1)]$ where $0 < b < 1$
c	=	$\{-0.001[0.461 + 0.0174(ADL) + 0.0114(ADH) - 0.0287(ADT)(MMP/1000)]\}$

and

RI_{TG1}	=	roughness at time TG1, in m/km IRI
RI_{TG2}	=	roughness at time TG2, in m/km IRI
RI_{max}	=	maximum allowable roughness for specified material, in m/km IRI
TG1, TG2	=	time elapsed since latest grading, in days
ADL	=	average daily light traffic (GVW < 3500kg) in both directions, in vpd
ADH	=	average daily heavy traffic (GVW ≥ 3500kg) in both directions, in vpd
ADT	=	average daily vehicular traffic in both directions, in veh/day
MMP	=	mean monthly precipitation, in mm/month
HC	=	average horizontal curvature of the road, in deg/km
RF	=	average rise plus fall of the road, in m/km
MDR	=	material gradation dust ratio
	=	P075 / P425 if P425 > 0
	=	1 if P425 = 0
P425	=	amount of material passing the 0.425 mm sieve, in per cent by mass
P075	=	amount of material passing the 0.075 mm sieve, in per cent by mass

Figure 5.3 illustrates the predicted increase in roughness with time for roads carrying different levels of traffic. In this example the input variables are as follows,

RI_{TG1}	=	5 m/km IRI
ADH	=	10% x ADL in vpd
ADT	=	ADH + ADL in vpd
MMP	=	150 mm/month
HC	=	180 deg/km
RF	=	50 m/km

The models can be calibrated for local conditions but it is unlikely that they will be able to discriminate between the performances of the different soils with sufficient precision for our purposes. This is because the models contain too few parameters. For example, the only material factor in the roughness performance models is the ratio P075/P425 where P075 and P425 are the percentages of material passing the 0.075 and the 0.425mm sieves. The effect of changing this from 0.5 to 0.75 (i.e. more fine material) is to increase the rate of deterioration slightly as shown in Figure 5.4

Thus if the critical level of roughness is defined as, say, 14 IRI, the time to reach this value decreases from 3.5 years to 2.5 years (in this example). The optimum performance occurs when the P075/P425 ratio is equal to 0.5. This broadly agrees with Figure 5.1 , corresponding reasonably well to the area labelled A if it is assumed that the P075 material has a moderate plasticity to provide cohesion. Nevertheless, the P075/P425 ratio alone is generally inadequate to explain all the effects of PSD and plasticity hence the power of the model to discriminate between materials is limited. However, the HDM equations also provide insight into the effect of road gradient on deterioration and this aspect is examined below.

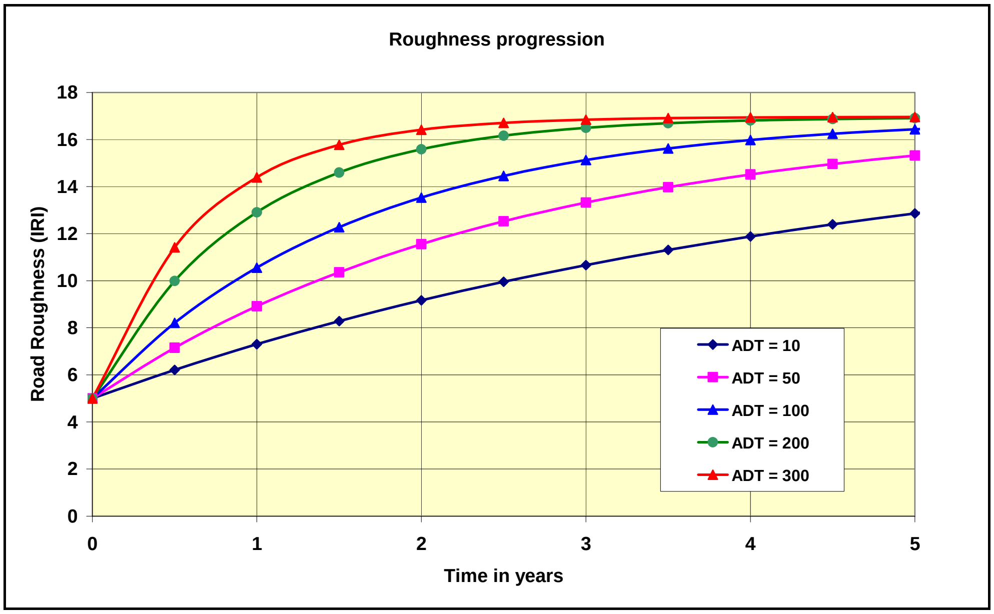


Figure 5.3 Roughness deterioration with time

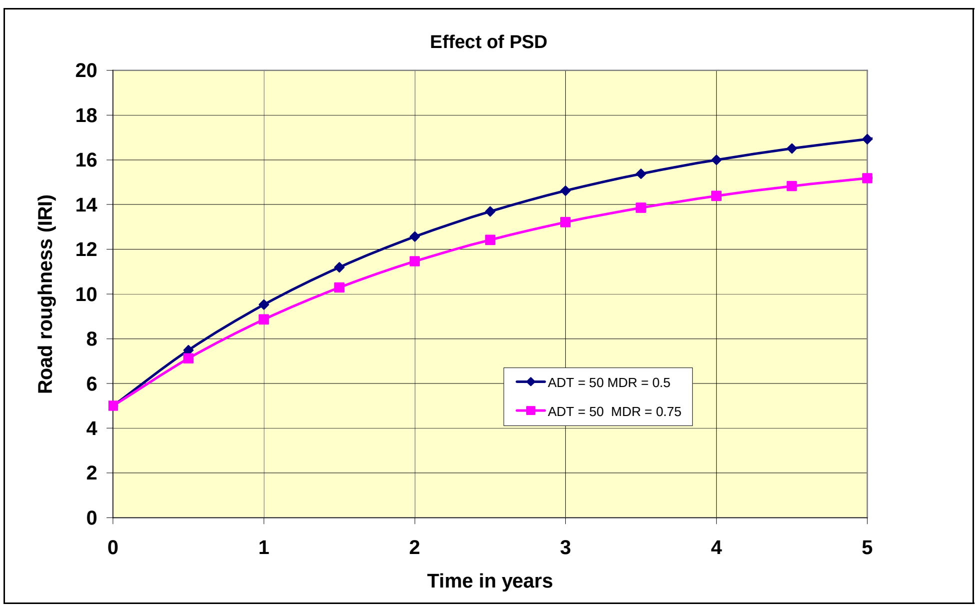


Figure 5.4 The effect of changing the PSD

The effect of compaction at the surface of the ENSR on the rate of deterioration is considerable. It should be noted that the unsealed road models in HDM were based on the behaviour of gravel roads which were maintained by grading but with no associated compaction. The process of grading loosens the material and hence relatively high rates of deterioration occur compared with the rates that would be obtained if the surfacing is also re-compacted at each grading operation.

In our case, modelling the performance from ‘newly constructed’ (when compaction would have been carried out), but with no subsequent maintenance grading operations, is equivalent to having a compacted surfacing and so the rate of deterioration will be initially lower than shown in the Figures above. Figure 5.5 shows the predictions of HDM 4 for the same conditions as in Figure 5.3 but with a well-compacted surface. The lower rate of initial deterioration is apparent.

The model also predicts that the difference in long-term performance between a compacted surface and a newly-graded but uncompacted surface is greater for high traffic than for low traffic. This is consistent with the idea that a compacted surface is better able to withstand traffic induced deterioration and that the effects of the environment are proportionately greater for low traffic but that they take longer to manifest themselves. It should be noted that the models have not been calibrated for the conditions in Cambodia and, as explained above, are not specifically based on the behaviour of ENSRs. The behaviour patterns described here should therefore be taken as indicative only and note taken of the factors that affect behaviour.

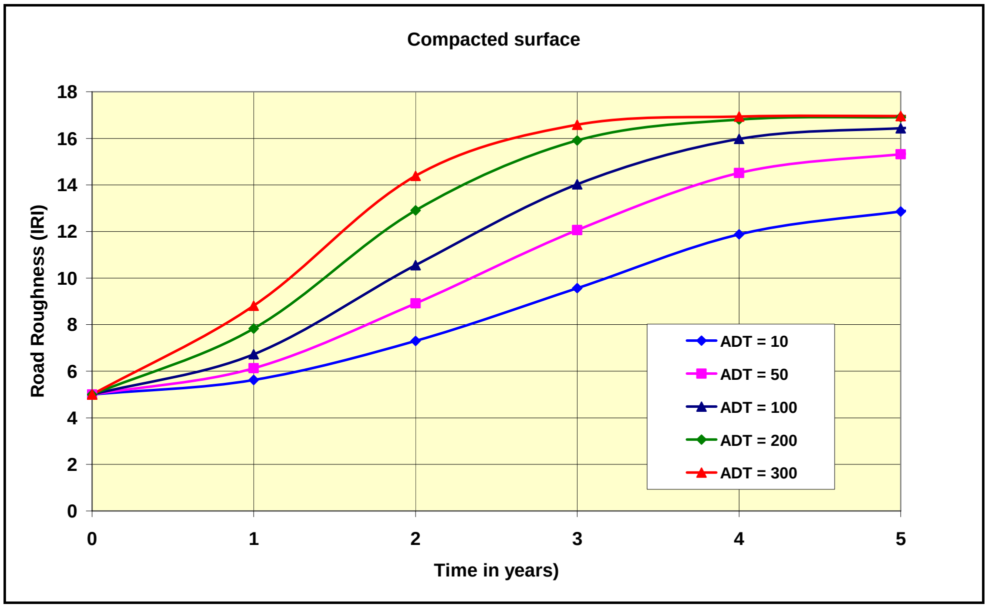


Figure 5.5 Roughness deterioration with compacted surface

5.5 Corrugations

Under some circumstances unpaved roads are prone to the phenomenon of corrugations. Material in the surfacing moves longitudinally to form waves of about 1 to 1.5 metres wavelength and up to 50mm amplitude. The materials that are prone to corrugations have PSDs within quite a broad range but corrugations form only under dry conditions and require moderate traffic levels. They have proved to be a difficult problem to solve in dry areas; the only way to prevent them appears to be by reducing tyre pressures to a very low value, a method that is impracticable on public roads. Corrugations do not constitute failure in the normal sense because the road remains trafficable, though the ride is very uncomfortable and vehicle operating costs can be very high. In whole life cost terms it is very likely that materials that are prone to corrugations would be too expensive and would be ruled out as an option. Corrugations are unlikely to be a major issue in the behaviour assessment of Cambodian low volume ENSRs.

5.6 Loss of surfacing material

The loss of material from the surface of a *gravel* road is a major concern and usually dictates the maintenance and upgrading strategy. In the HDM models the loss of surface material is caused primarily by the action of traffic. The models for predicting this in HDM include the plasticity of the material as the only explanatory *material* variable. However, rainfall and geometry are also important. The equations are as follows;

$$MLA = K_{gl}\ 3.65[3.46 + 0.246(MMP/1000)(RF) + (KT)(AADT)]$$

where,

$$KT = K_{kt} \max [0,\ 0.022 + 0.969(HC/57300) + 0.00342(MMP/1000)(P075) - 0.0092(MMP/1000)(PI) - 0.101(MMP/1000)]$$

and

MLA = annual material loss, in mm/year

KT = traffic-induced material whip-off coefficient

AADT = annual average daily traffic, in veh/day

MMP = mean monthly precipitation, in mm/month

RF = average rise plus fall of the road, in m/km

HC = average horizontal curvature of the road, in deg/km

PI = plasticity index of the material, in per cent

K_{gl} = calibration factor for material loss

K_{kt} = calibration factor for traffic-induced material whip-off coefficient

Figure 5.6 to Figure 5.11 illustrate some of the effects for a non-plastic material. For the particular material illustrated, Figure 5.6 shows that, in hilly terrain, as rainfall increases from 100 to 200mm/month, the loss of material loss increases by 10 - 15 mm/year. The effect of increasing the traffic by about 150 vpd gives a similar increase in material loss. In rolling terrain (Figure 5.7) rainfall has less effect, material loss increasing by about 5 - 7 mm/year as rainfall increases from 100 to 200 mm/month. In flat terrain the effect of rainfall is predicted to be even less as shown in Figure 5.8.

Figure 5.9 to Figure 5.11 illustrate the predictions for a much finer and more plastic material. The trends are similar to those for the coarser, non-plastic material but, perhaps surprising, the magnitude of the loss of material is only slightly greater.

It should be noted that the traffic levels in these Figures refers to total ADT. On the experimental roads on which much of the model equations were based, this was predominantly cars, pick-ups and trucks. In general, the data were not derived from roads carrying a large number of motorcycles, motorcycle trailers and bicycles. For such roads the models are not expected to give accurate values but the trends with each variable ought to be similar.

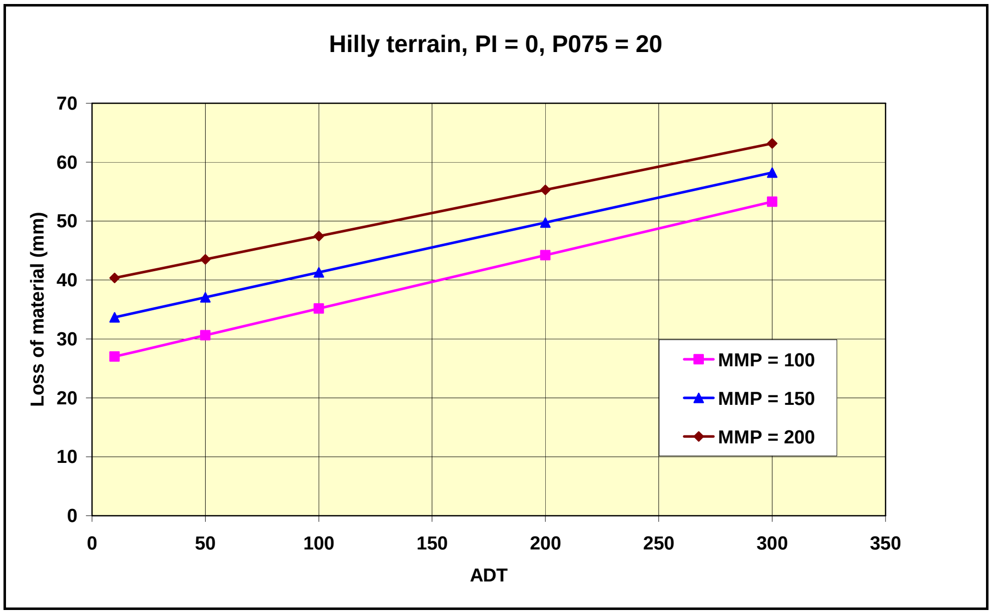


Figure 5.6 Loss of material (PI = 0, P075 = 20%) in hilly terrain

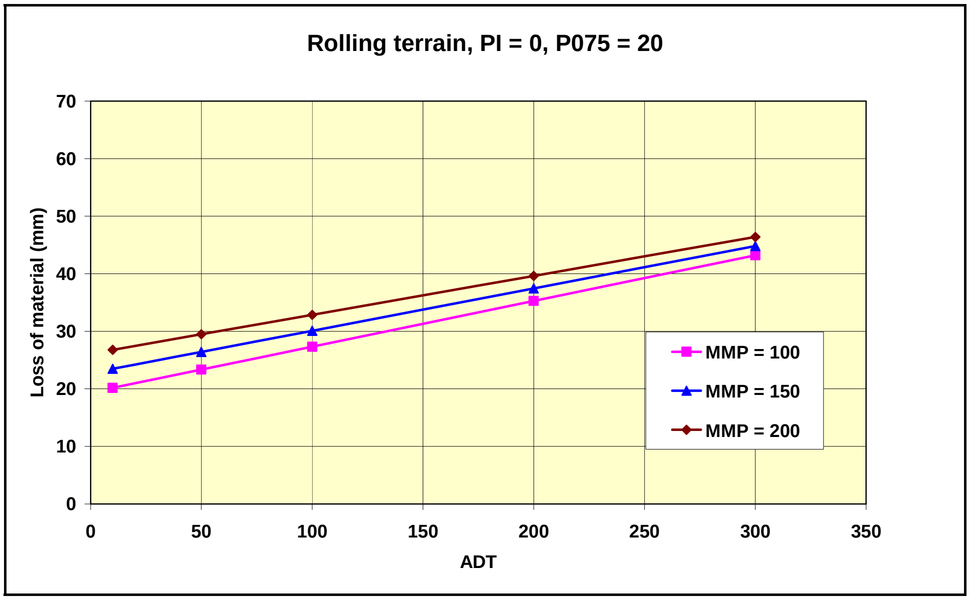


Figure 5.7 Loss of material (PI = 0, P075 = 20%) in rolling terrain

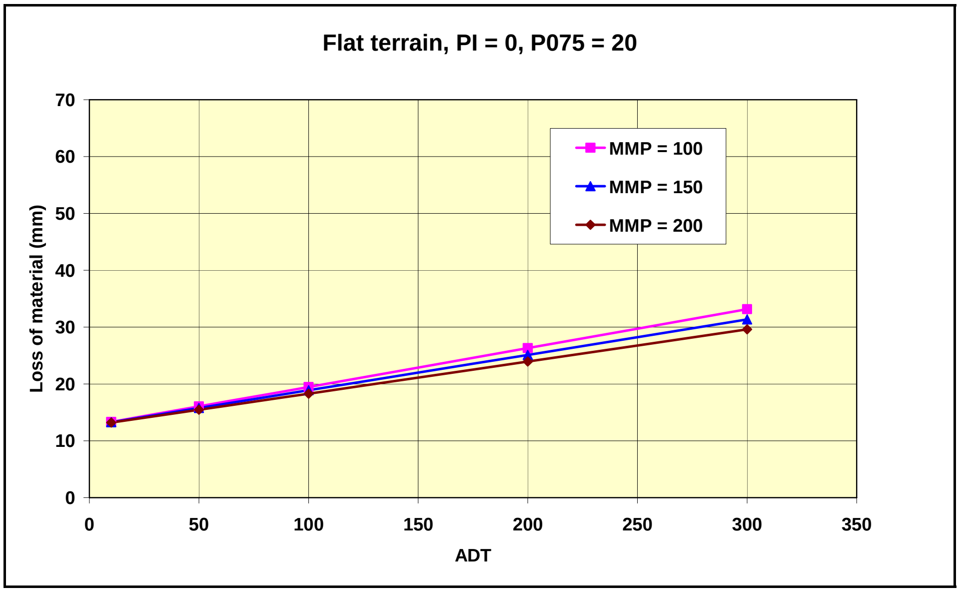


Figure 5.8 Loss of material (PI = 0, P075 = 20%) in flat terrain

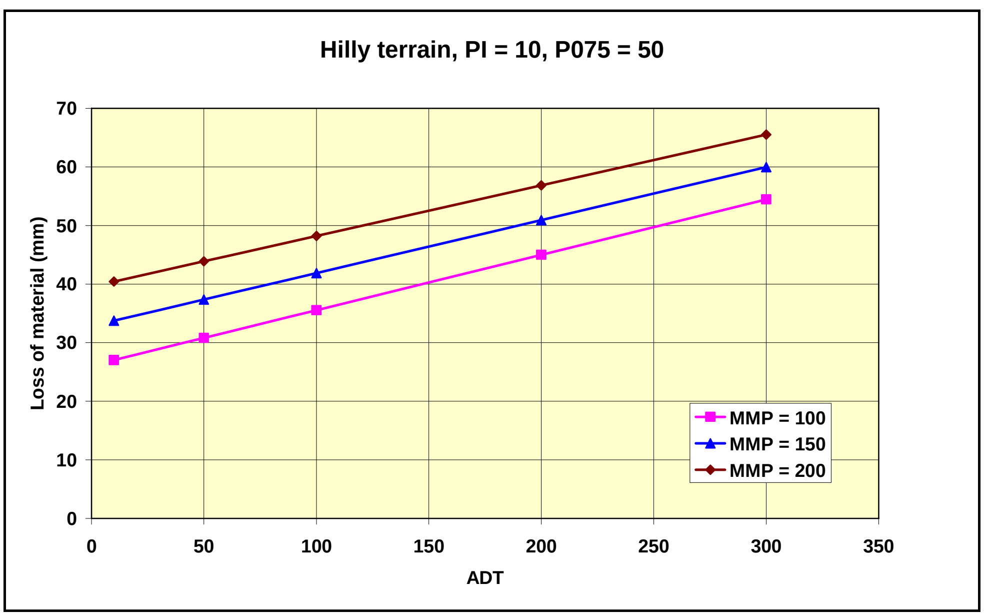


Figure 5.9 Loss of material (PI = 10, P075 = 50%) in hilly terrain

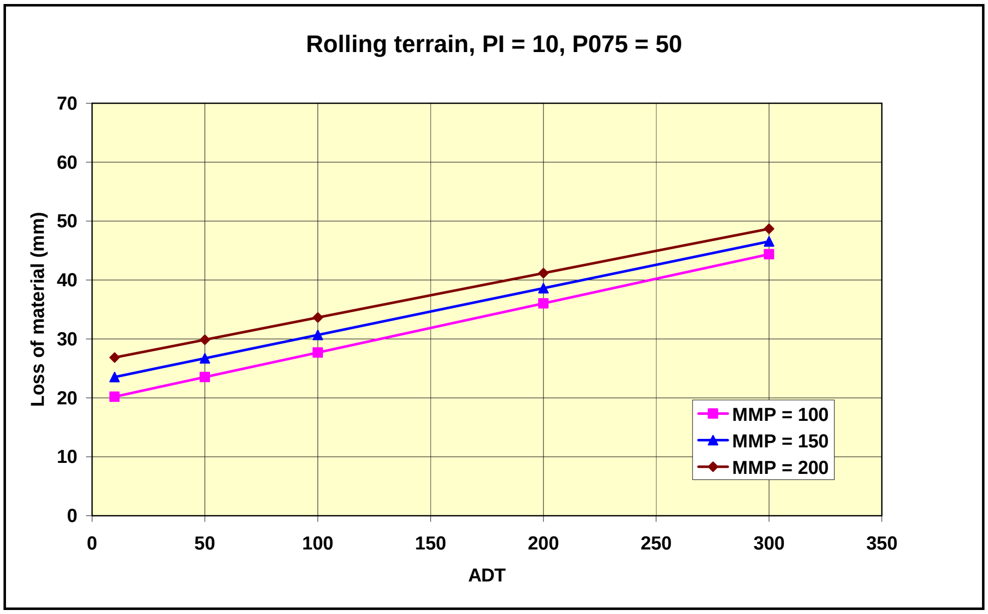


Figure 5.10 Loss of material (PI = 10, P075 = 50%) in rolling terrain

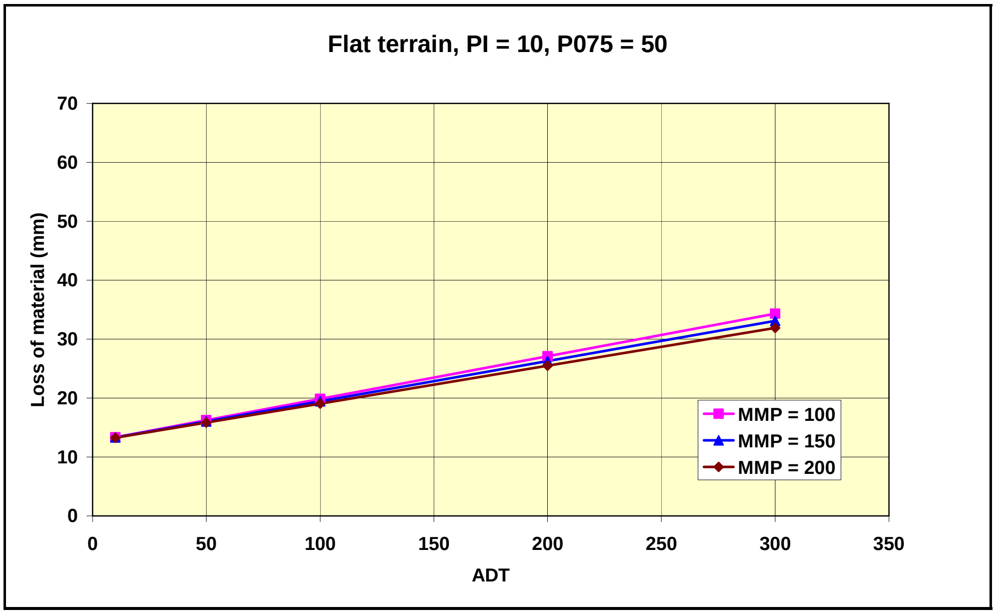


Figure 5.11 Loss of material (PI = 10, P075 = 50%) in flat terrain

Experiences in Vietnam (SEACAP 4) have shown that rates of gravel loss can be considerably higher than predicted by HDM 4 and were generally related to such factors as high rainfall, flooding, material type and terrain rather than predominantly to traffic. There are several probable reasons for this. First of all the HDM equations are based on empirical evidence from more moderate climates and less severe topography where erosion effects were much less important than the traffic effects caused by generally heavier traffic than that which runs on LVRRs in SEA. Secondly, inadequate maintenance was also identified as a factor in the SEACAP 4 study and contrasts with active road maintenance on many of the roads whose performances are described by the HDM4 relationships. Models for predicting the gravel loss from the sites in Vietnam remain to be developed from the SEACAP 4 database, although general regional gravel loss figures have been derived for whole life costing purposes, Table 5.1(Cook and Petts, 2004)

For ENSRs it is assumed that loss of any surface material can also be high although it is doubtful whether these losses can be predicted using the 'gravel' equations in HDM. Furthermore the effects of erosion are likely to be much greater. For gravel surfaces, the loss of gravel results in the need to import more gravel. Similarly, it is necessary to restore the height of the running surface of ENSRs and to maintain adequate camber using the available material at that location. Failure to do this results in 'sunken' road profiles that begin to act like drainage channels.

5.7 Effect of road geometry

Road geometry has a considerable effect on the performance of unsealed roads. Unfortunately much of the research on performance has been based on the behaviour of roads in relatively flat terrain. The reason for this is that it was important to carry out such research first but, partly because of the complexity of the problem, insufficient effort has been devoted to more extreme conditions. Thus the models in HDM may not reflect the conditions in much of SEA and the models may be therefore be inadequate.

Table 5.1 Vietnam Gravel Loss (no maintenance)

Terrain Region	**Low delta/coast. Subject to flood**	**Low delta/coast. Minimal flood**	**Inland flat**	**Rolling small hills**	**Hilly and mountaineous**
Basic Gravel Loss (mm/year)	40	25	30	20	35
Key Regional Factors	Poor quality material	Poor quality material	Poor quality material	Gradient	Sheet erosion See Note
Adjustment to basic loss for regional factors	Add 15mm/year	Add 5mm/year	Add 10mm/year	2-4% add 5mm/year 4-6% add 10mm/year	A: add 5mm/year B: add 15mm/year C: add 30mm/year

Notes: Sheet erosion definition; A = Gradient < 2% subject to minor sheet flooding

B = Gradient 2-4% subject to regular sheet flooding

C = Gradient > 4% subject to regular sheet flooding

Sheet flooding means that water covers the road surface due to flooding from surrounding ground and not just the rainwater that falls directly on the road surface.

Sector ‘rules of thumb’ recommend that gravel roads are not constructed at longitudinal gradients of more than 6% (e.g. R Millard (1993) *Road making in the tropic: materials and methods*). At higher gradients the longitudinal gradient is substantially steeper than the crossfall and the general direction of the water runoff is along, rather than off, the surface. Any irregularity in the surface can accentuate this effect and the water picks up any loose material to rapidly erode the surface into roughly longitudinal channels. It is likely that more stringent restrictions should be placed on certain combinations of rainfall and gradient for ENSRs in SEA pending local research into this issue.

Crossfall is an important feature of the geometry of ENSRs. At below about 2% there is a risk that water will pond locally and pothole development will be initiated. At above about 7%, lateral erosion and the safety and stability of vehicles become issues. The usual recommendation is to construct and maintain unsealed surfaces at between 4 and 6% crossfall.

5.8 Loss of traction or slipperiness

Low traction, lack of friction or slipperiness is not specifically associated with deterioration but for ENSRs it is a critical parameter which determines the number of days that a road can be trafficked. Table 2.1 Definitions of basic access service levels for ENSRs shows the conditions for defining basic access. Condition A is concerned with this but was specifically aimed at the time required for water levels to fall sufficiently for all water crossings to be trafficable. However, in the wet climates of SEA there are periods of the year when rainfall can occur so frequently that roads can be too slippery for traffic for much longer periods than 24 hours. Here we are discussing roads with adequate camber and good overall shape; in other words roads that are newly constructed. As indicated in Section 4.3, this behaviour can be associated with inherent characteristics of the road materials which may be related to a combination of mineralogy and fabric. Such roads may not be viable if they are too slippery for too long.

In general, many old roads have deteriorated so much that they lack camber and shape. At this level of deterioration, water ponds for many days in vulnerable places. Such spots deteriorate quickly and the affected area can become impassable. This is a maintenance issue and not directly related to the viability of the basic design unless, of course, such deterioration occurs too quickly after construction because of inadequate materials, too much traffic or some other design fault.

Research has shown that impassability resulting from loss of traction between vehicle wheels and the road on a well-shaped ENSR will occur on all roads whose surfacing comprises predominantly clay material whenever a minimum depth of rain falls onto the surface. This level of rainfall is typically the amount that would fall in an average intensity storm of more than about 30 minutes duration, although the precise impact will be a function of mineralogy, fabric and structure. Thus the number of days each year that such a road will be impassable for some of the time depends simply on the number of days that such a storm occurs. If such storms occur too frequently then there will be insufficient time for the road surface to dry and so the period of impassability will be correspondingly longer.

Experience with an ENSR maintenance programme in East Africa found that within three hours of rain ceasing on a well-cambered lateritic clay soil, the surface was usually drained and dried out sufficiently to bear medium truck traffic. Investigations would be informative relating to the local soils, climate and traffic conditions in Cambodia.

Maps showing contours of equal rain days superimposed on a soil map are helpful in evaluating the potential loss of access for roads in different areas of the country.

5.9 Maintenance

The HDM models also concentrate on the effects of grading the unsealed roads to improve roughness and to minimise gravel loss. On the unsealed roads in Cambodia grading is not being considered as a regular maintenance option at the moment. The viability of ENSRs are being considered in terms of the length of their likely durability without periodic maintenance, but the type of maintenance that can be done in the provincial areas will need to be assessed and its effectiveness evaluated during field surveys.

Important issues to be addressed in developing an effective maintenance strategy for ENSRs in the Cambodian environment are:-

- The types of vehicle that require access and their characteristics with respect to road deterioration
- Acceptable interruptions of access through the year (social and economic)
- The types of soil and the rates of deterioration of the key characteristics that affect access
- Suitable maintenance intervention criteria
- The technical options for carrying out the maintenance (including labour and intermediate equipment)
- Organisational options and possible responsibilities for road maintenance
- Resources and funds required for ENSR maintenance
- Acceptable and achievable levels of service

For designs that are ‘promising’ the next stage of the study will involve whole life costing with appropriate maintenance alternatives.

6 CONCLUSIONS

The foregoing review has attempted to identify the parameters that determine the performance of ENSRs. The next stage of the project is to survey a sample of existing ENSRs in Cambodia. Sections of road that have performed well and sections that have performed badly need to be sampled and their characteristics recorded in order to determine the relative importance of each factor and to define the conditions that need to be met for an ENS to be viable. In other words, which sections of a road can be of ENS standard and which need to be of higher standard to create a complete road of compatible trafficability and durability. The factors listed in the following Table 6.1 need to be measured. The shaded rows refer to properties that need to be measured in the laboratory and therefore to the need for samples to be collected from the site.

Table 6.1 Factors affecting the performance of ENSRs

Property	Units	Comments
Material Properties		
Material description or type		The PSD will determine the material nomenclature, e.g. clay, sand etc. Any additional information should be recorded here.
PSD - Particle size distribution	%	Ensure sieve sizes allow derived parameters to be calculated e.g. plasticity product, grading modulus
Oversized material	Yes/no?	Likely to adversely affect roughness
Linear shrinkage or Atterberg limits	%	To obtain plasticity. Linear shrinkage preferred
Soaked CBR at standard AASHTO compaction	%	Essential for defining critical values

Carriageway properties		
Embankment	m	Height above drain invert
Ground shape		Draw – flat, sidelong etc
Longitudinal gradient	%	Measure with an Abney level or other rapid system
Camber	%	String line and depths (maybe)
Horizontal alignment	degrees	Road curvature at test point
Width	m	Care required to define width of running surface
Drainage properties		
Surface drainage characteristics		Ability to shed water (a combination of camber and rut depth)
Existence of side drains		Nature of side drain
State of side drains		– working, silted, blocked etc
Water table level		Current
Water table		Estimated maximum or flood frequency
Quantification of deterioration		
Rut depth	mm	Maximum value at test point
Erosion in running surface	mm	Erosion channels maximum depth and number
Corrugations	mm	Presence at test point and amplitude
Potholes	m^2	Presence at test point
Loose material	mm	Assessment of thickness

A suitable survey form is being developed and tested. The next task is to identify roads for surveying and to facilitate this, communication with the provincial road authorities has been initiated.

7 Acknowledgements

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