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CONSTRUCTION AND MAINTENANCE OF EMBANKMENTS USING HIGHLY ERODIBLE SOILS IN THE PILBARA, NORTH-WESTERN AUSTRALIA

J.V. Smith[1] and L.A. Sullivan [2]
[1]School of Civil, Environmental and Chemical Engineering, RMIT University, Australia; [2] Southern Cross Geosciences, Australia

ABSTRACT: Many soils and sediments in the Pilbara region of north-western Australia are highly susceptible to erosion. Large quantities of construction materials are required as iron ore mining and the extensive railway lines used to transport ore to port continue to be developed in the region. Simply avoiding the use of highly erodible materials is often considered to be too high a cost where alternatives are scarce. Constructing embankments to survive the cyclonic wet season from material highly susceptible to erosion, is a major challenge. Highly erodible materials encountered in the Pilbara include some bedrock shales, dispersive alluvial silts and sands and slaking clays and mudstones. Dispersive materials can erode internally by the formation of pipes or tunnels. Piping erosion can be difficult to detect and can cause severe internal damage to embankments before being detected. Similarly, slaking material can undergo compaction during wetting and drying cycles resulting in unexpectedly large settlements. The effect of erosion, in general, is controlled by appropriate embankment design and construction, in particular compaction standards. Erosion controls include sacrificial batters, surface protection, encapsulation and stabilisation. For many mining projects achieving short-term construction deadlines is a high priority and adding erosion control measures after construction may be preferred. Predicting the time by which erosion control needs to be installed or rehabilitated should be a part of the embankment design process. Material selection has direct implications for the on-going asset management of embankment structures.

Keywords: Embankment, Erosion, Dispersion, Slaking, Pilbara

1. INTRODUCTION

Many soils and sediments in the Pilbara region of north-western Australia are highly susceptible to erosion. Large quantities of construction materials are required as iron ore mining and the extensive railway lines used to transport ore to port continue to be developed in the region. Constructing embankments to survive the cyclonic wet season from material highly susceptible to erosion, is a major challenge. Simply avoiding the use of highly erodible materials is often considered to be too high a cost as alternatives are scarce.

Highly erodible materials encountered in the Pilbara include some bedrock shales, dispersive alluvial silts and sands and slaking clays and mudstones. Dispersive materials can erode internally by the formation of pipes or tunnels. Piping erosion can be difficult to detect and can cause severe damage to embankments before being detected. The effect of erosion can be controlled by appropriate embankment design, construction and maintenance. Erosion controls include sacrificial batters, surface protection, encapsulation and stabilisation.

For many mining projects achieving short-term construction deadlines is a high priority and adding erosion control measures and maintenance after construction is often preferred. Predicting the time by which erosion control needs to be installed or rehabilitated should be a part of the embankment design process. Material selection has direct implications for the on-going asset management of embankment structures. Field observations and laboratory tests show that the coastal and fluvial sediments, dominated by the silty 'Pindan' sand, contain dispersive clays, which are prone to erosion even where clay content and sodicity is low.

Conventional lime stabilisation would be impeded by the alkaline condition of the soil. In contrast, tests show gypsum can achieve 0% Exchangeable Sodium Percentage (ESP) with applications less than 100 grams per ton of soil. The use of gypsum in embankment stabilisation is novel and requires further investigation. In agricultural applications gypsum provides a permanent control on dispersion by the replacement of sodium and magnesium with calcium and also has a temporary 'electrolyte effect which may last from two to five years depending on water movement. The 'electrolyte effect' is temporary which is not normally acceptable in civil engineering projects. However, the very low initial ESP of these materials indicates permanent stabilisation will be achieved by additions of even minimal quantities of gypsum. The dynamic nature of mining infrastructure projects means that gaining an additional life prior to rehabilitation works can represent a significant financial incentive.

The Pilbara region is undergoing rapid expansion of railways and other transport infrastructure to link the inland mines with ports to the north. The Economic Regulation Authority [1], the independent economic regulator for Western Australia, has factored in a 100 year life when estimating the asset value of for railway earthworks, including some in the Pilbara. Meanwhile, construction is occurring at record rates with an emphasis on low cost construction. From an asset management viewpoint, there is inevitably a trade-off between up-front construction costs and on-going maintenance costs which should be made explicit during the design process [2].

A detailed understanding of soil behaviour is fundamental to predicting the durability of embankments constructed from soils and sediments of the Pilbara region.

2. MATERIAL TYPES

The geology of the Pilbara region comprises bedrock of banded iron formation (BIF), consisting of alternating layers of chert, siltstone, mudstone and haematite in varying proportions, shale (referring generally to interbedded fine sandstones, laminated siltstones and mudstones), dolomite, and thick sequences of basic and acidic igneous rocks. According to a regional study, formations in the Pilbara prone to erosion include the Weeli Wolli Dolerite, Mt McRae Shale, Mt Sylvia Formation shales, Bee Gorge Member shales, and various other granites and basalts [3]. The implications of the erodible nature of these materials on borrow pit stability has been investigated [4].

Materials overlying bedrock include alluvial gravels, sands, silts and clays in fans, channels or on flood plains. Colluvial and taluvial sands, gravels and boulders occur on slopes. In the northwest part of Western Australia, scree gravel slopes comprised of materials useful for construction purposes can be expected near outcrops of chert, quartzite and banded ironstone, whereas, deposits of gravel on slopes over dolerite, basalt and other dark igneous rock should be treated with caution because of highly active (montmorillonitic) clays which, they state, almost always occur in the gravel fines or overburden [5]. Weathering profiles developed on bedrock and unconsolidated sediments can be clay-rich or have siliceous or ferruginous duricrusts.

According to the Department of Main Roads of Western Australia [5], well graded sand with small amounts of clay has been extensively used as basecourse in the northwest of the State. The red coloured sands are often referred to as “pindan” and the yellow coloured sands are sometimes called “wodgil”.

Investigations for the Broome Airport [6] described the pindan sand as a collapsible silty-sand or clayey-sand soil, typically red in colour. Pindan sand is usually considered deleterious, but may display a self-cementation property upon dry-back during construction. The substantial strength gain upon drying, which is lost upon re-wetting, was thought to be due to the bridging effect of clay in the pindan sand. Previous work also attributed the effect to iron oxide, and further evidence from the laboratory testing has suggested that the bridges also form from Fe-kaolinite which contains both iron and aluminium (hydr)oxides. Suction testing suggests that the strength gain of the pindan upon dry-back is not just due to the cementing action of the bridges, but is also due to increased suction from the changed void geometry after the bridges have formed.

A review of approximately 50 laboratory tests of pindan sand material from south of Port Hedland for this study found that gradings were consistent but Atterberg limits were variable with most samples exceeding the recommended value (Table 1).

3. EMBANKMENT CONSTRUCTION IN THE PILBARA

A review of the construction of railway embankments in the Pilbara [3], described embankments up to 45 m high constructed of rockfill typically compacted in lifts of 750–1000 mm thickness with about 10% by weight of water added during placement. The design slopes of these high rockfill embankments are typically based on precedent with angles of 1.5 horizontal to 1 vertical, that is, 34°. A settlement value of 1% for the embankment height has been considered appropriate and is allowed for by cambering and by increasing the crest width so that an increased thickness of ballast can be applied to compensate for long-term settlement [3].

When durable and non-durable (slaking) rocks in embankments are subjected to compressive contact forces in the presence of water, the non-durable rock fragments are converted to soil that moves into the space between the durable rock fragments causing the settlement of the embankment [7]. Their study calculated the amount of settlement experienced by a mixture of non-durable shale with durable rock fragments subjected to embankment loads. The amount of settlement varied with the percentage by weight of the shale in the mixtures. The greatest settlements were recorded in 100% shale.

It has been observed that shortfalls in suitable borrow material commonly occur in railway construction projects in the Pilbara [3]. This situation is due to variations in overburden depth, incursions of unsuitable materials and environmental constraints such as a need to keep borrow pits shallow to allow drainage and prevent water ponding.

Table 1: Test results reviewed for this study (approximately 50) relative to published pindan sand recommended interim criteria for use as a sub-base or selected subgrade in a semi-arid or arid climate [6].

Test	Criteria	Proportion of samples meeting criteria
Sub-base DCP-CBR after dry-back	≥40	59%
Select subgrade DCP-CBR after dry-back	≥20	74%
Sub-base Compaction density (Modified MDD)	95%	Not tested
Select subgrade Compaction density (Modified MDD)	93%	Not tested
Grading %passing 425μm sieve	30-100	98%
Grading %passing 75μm sieve	15? – 40 (1)	92%
PI x %passing 75μm sieve	> 150	87%
Liquid limit %	≤25	51%
Plasticity index %	4-12	32%
MDD modified t/m^3	≥2.0	Not tested
OMC %	5-10	Not tested
Al2O3 + Fe2O3 %	>8	Not tested

1. The lower limit is not known. Some of the better performing pindan sand had %passing 75μm sieve >25, and this may be a guide for sub-base quality. However it is suggested that the characterisation of suitable pindan should be done by strength testing or the use of PI x %passing 75μm sieve rather than grading alone [6].

3.1 Erosion of Embankments

Appropriate material selection and compaction is intended to protect embankments from scouring erosion from the wash of surface water during heavy rainfall. Armouring around bridge abutments and culverts is typically installed to protect embankments from sheet flow and flooding.

Erosional processes which can be more difficult to control are those which occur by internal erosion of fine particles by water infiltrating through the embankment. Evidence of this type of erosion is often concealed until the collapse of pipes or tunnels which have formed below the surface.

Figure 1A shows an embankment constructed from gravelly soil with deep surface scouring. Bridges of soil are present over some of the scours indicating that erosion is, at least in part, a sub-surface process. The scouring is concentrated in a band approximately 1.5 m above the base of the embankment suggesting that either the material type or the construction method at that level was the cause of the erosion.

Figure 1B shows an embankment constructed of silty sands with narrow surface scours. Local erosion of the embankment toe by surface water has revealed that open channels of piping erosion 250 mm across had formed within the embankment.

Embankment slope design should not only take into account stability against slumping but also the role that the slope angle plays in controlling erosion. Slopes of 1.5 horizontal to 1 vertical (34^{o}) may be too steep for embankments constructed of non-cohesive silty sands as this angle can be expected to be close to the friction angle of such sands.

The role of vegetation in embankment stabilisation has been considered elsewhere [8] but will not be considered here due to the climatic limitations on vegetation growth in the Pilbara region.

3.2 Sacrificial Batters

A commonly applied approach to the use of highly erodible materials is to add additional mass to embankments to delay the impact of erosion on the critical part of the embankment. The additional mass may be in the form of flatter batters or wider crests. Ideally, this approach should incorporate an estimated erosion rate and a predicted lifetime at which rehabilitation is expected to be required. There should also be survey-based monitoring of the actual erosion losses so that predicted performance can be validated. The occurrence of piping erosion, in particular, can occur without equivalent surface scouring being visible.

Figure 2A shows an eroding embankment being managed by the construction of a buttress embankment constructed to approximately half the height of the existing embankment. The width of the buttress is determined by the need to accommodate construction equipment and greatly exceeds the width necessary to provide erosion control. However, the same construction material is being used and the buttress should be considered sacrificial as it is expected to develop similar erosional problems.

3.3 Surface Protection

Surface protection can be applied at the time of construction or later as rehabilitation. Figure 2B shows the application of geotextile with a physical and ultraviolet barrier of rock rip-rap. In this case, the surface protection is a rehabilitation measure not anticipated in the original project. Figure 3 shows an example drawing of such surface protection works.

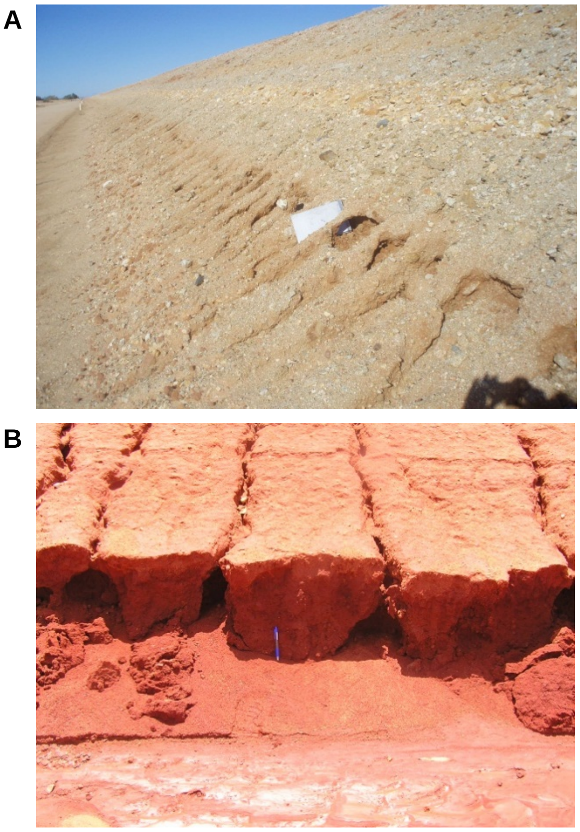

Figure 1. Piping-type erosion on embankments in the Pilbara. A) Concentration of piping erosion at a horizon within the embankment constructed of weathered granite. An A4 size folder shows the scale and highlights the presence of soil bridges in the deeply eroded part of the embankment. B) Fine surface runnels approximately 300 mm apart overlie erosion pipes in an embankment constructed of alluvial sands.

Figure 2C shows surface protection which has been applied in a more *ad hoc* manner by dozing of blasting spoil against eroding batters. Figure 2D shows that in the absence of geotextile or where the applied materials are uniformly coarse, fine soil in the embankment readily washes through this type of protection.

3.4 Encapsulation

In a review of engineering geology for railway construction in the Pilbara [3], it was recommended that weathered shale or dolerite bedrock which can be prone to erosion should be encapsulated by 2 m of non-erodible soil. Encapsulation introduces the potential problem of differential settlement across embankments and requires significant material investigations and trials to be conducted.

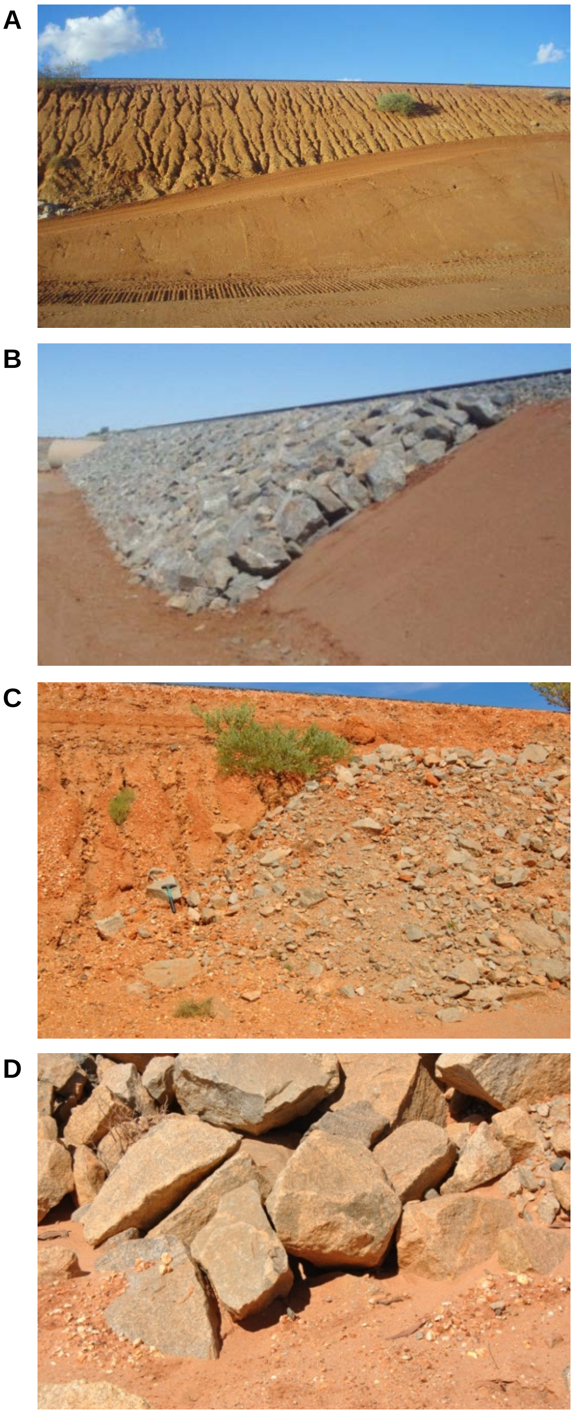

Figure 2. Post-construction rehabilitation of eroded embankments. A) Extending the width of the earth embankment to control embankment erosion. B) Placement of geotextile and rip-rap. C) Excess blast spoil dozed against embankment face to control embankment erosion. D) Fines appear to readily migrate through the improvised rip-rap shown in photograph C.

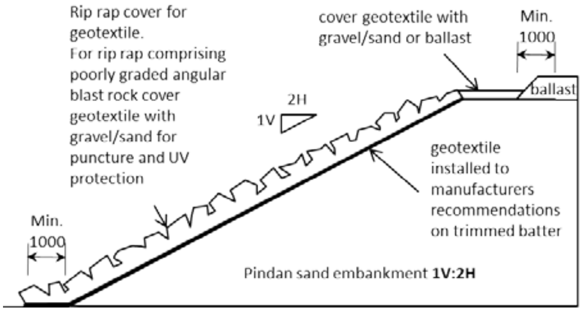

Figure 3. Example detail of recommended geotextile and rip rap protection on erodible embankments.

3.5 Stabilisation

Stabilisation of low plasticity soils with agents such as lime and cement is well documented [9]. Soil stabilisation has been used in the Pilbara on various projects. For example, the stabilisation of highly reactive clay soil known as gilgai soil for the Karratha to Tom Price road [10]. In that study, hydrated lime and a combination of lime and cement were found to have a significant effect in improvement of California Bearing Ratio, unconfined compressive strength and shrink and swell characteristics of the reactive subgrade material.

A case of study ground improvement was undertaken at the stockyard berms of a large iron ore handling facility located in the Pilbara region [11]. The stabilisation involved addition of 3% cement to the berm materials carried out in situ using a Bomag stabiliser machine. Plate load tests were undertaken to assess degree of ground improvement of the clayey gravels. Cement not only provides physical strengthening of a soil but also contributes calcium to the chemical balance in the embankment which can exchange for sodium on clay and thereby influence erodibility of dispersive soils. The role of cement as a chemical stabiliser requires further investigation.

Tests conducted at the Southern Cross GeoScience laboratory have shown that some of the silty pindan sands of the Pilbara contain dispersive clays. The tests indicated that this soil must be managed carefully to avoid structural problems such as crusting and erosion. These findings indicate that the soils are likely to be prone to dispersive erosion even if their clay content and sodicity are low. Stabilisation of embankment soils with mineral additives may provide significant improvements in erosion susceptibility. Conventional lime stabilisation can be impeded by the alkaline condition of the soil which inhibit the release of calcium from the lime. Alternatively, gypsum releases calcium more readily in alkaline conditions. Gypsum is typically only used to control dispersion of soil in agricultural practice due to the anticipated short-term effect [12]-[15], however, the use of gypsum in embankment construction has been proposed [16].

Tests at Southern Cross Geosciences on dispersive soils from the Pilbara found that an Exchangeable Sodium Percentage of near 0% could be achievable with extremely low applications of less than 100 grams of gypsum per ton of soil. The use of gypsum in embankment stabilisation is novel and requires further investigation. In agricultural applications gypsum provides a permanent control on clay dispersion by the gradual exchange on the clay of the two ‘dispersion causing’ cations sodium and magnesium, with the more stable calcium cation derived from gypsum dissolution. In addition, gypsum provides a fast acting, but temporary, control on dispersion via the ‘electrolyte effect’. The electrolyte effect is due to the flocculating effect of the higher salinity in water caused by gypsum dissolution and may last from two to five years depending on water movement. The electrolyte effect, being temporary, is not normally acceptable in civil engineering projects, but this effect serves to provide effective control during the period of cation exchange that leads to permanent dispersion control. Of course, the dynamic nature of mining infrastructure projects means that gaining even an additional 2-5 years of life prior to rehabilitation works can represent a very significant financial incentive.

Table 1: Summary of erosion controls for embankment construction

Control	During construction	Rehabilitation
Sacrificial flanks	Yes	Possible
Encapsulation	Yes	Possible
Stabilisation	Yes	Possible
Surface Protection	Yes	Yes

4. CONCLUSIONS

The use of highly erodible material to construct embankments is generally discouraged so that embankments are of high quality and longevity. However, the demand for short construction times means that the most abundant materials at hand will often be used in construction. Consequently, some form of erosion control will be required during or soon after construction. Erosion control may be in the form of surface protection, encapsulation or stabilisation. Surface protection can be conducted as part of the original construction or as later rehabilitation. Encapsulation requires good quality material to be available or stabilisation of material for the outer part of embankments. Stabilisation has been applied on some previous projects in the region and further investigations are required. Given the need for many projects to achieve short-term deadlines for construction, it is likely that a significant amount of highly erodible materials will continue to be used in embankment construction. Erosion control and/or embankment rehabilitation will continue to be an integral part of infrastructure management in the Pilbara region.

5. ACKNOWLEDGEMENTS

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Corresponding Author: J.V. Smith