What is a sodic soil? Identification and management options for construction sites and disturbed lands

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Synopsis

There are large areas of soils in Australia which have developed on sedimentary parent materials containing high amounts of sodium. Sodic soils are traditionally defined as having an exchangeable sodium percentage (ESP) of greater than 6%, but there are many soils with lower sodium levels which exhibit similar behaviour under various conditions. Soils with high ESP levels and low electrolyte concentrations are unstable and exhibit a range of properties including weak aggregate stability, spontaneous dispersion, surfaces which seal and crust, the formation of hardsetting layers and low hydraulic conductivities. These characteristics lead to a range of problems for construction sites, including high water run-off and erosion rates, tunnel formation, reduced workability, difficulty with vegetation establishment, and reduced vegetation growth due to low water holding capacity and root penetration. Key management practices to reduce the impacts of sodic soils include: the management of surface water flows and minimisation of the potential for localised ponding, the use of compaction within the soil profile to reduce infiltration and minimise changes in the soil electrolytes which lead to spontaneous dispersion and tunnelling, and the use of amendments (eg. gypsum, organic matter, polyacrylamides) to modify either the ESP or directly influence aggregate stability.

Introduction

Salt affected soils occur both naturally and as the result of man's modification of the hydrologic processes which mobilise and accumulate salts within the landscape. Australia has large areas of naturally occurring salt affected soils and an increasing area influenced by man's activities. However, it should be noted at the outset that there are two broad classes of salt affected soils. Saline soils are those with an elevated concentration of any kind of salt, whereas "sodic" soils are those soils with a high proportion of sodium ions relative to other cations in the soil or water. Only sodic soils will be discussed in this paper. The issue of saline soils will be covered later in this conference by Gordon (2003).

A large proportion of land disturbance activities, including road construction, occur on sodium-affected soils. Soils with high levels of exchangeable sodium and low levels of total soluble salts are susceptible to clay dispersion which leads to sealing, crusting, low permeability, high bulk density and low porosity (eg. Rengasamy *et al.*, 1984). Sodic soils also tend to have a high soil erodibility due to the susceptibility of these soils to gully and tunnel erosion. Hence, it is appropriate that professionals working in the road construction, urban development and disturbed land management areas have some familiarity with the properties, development constraints and management practices appropriate for these soils. This paper provides an introduction to sodic soils in Queensland, describes the dispersion process, provides an overview of the methods for identifying dispersive soils, and highlights some of the field problems and management practices associated with dispersive soils.

Defining Sodicity

A wide range of parameters are used to describe soil chemical properties appropriate to the study of sodic soils. The exchangeable sodium percentage (ESP) of the soil is defined as:

$$\text{ESP} = (\text{exchangeable Na} * 100) / \text{cation exchange capacity} \qquad (1)$$

or

$$\text{ESP} = (\text{exchangeable Na} * 100) / \sum (\text{exchangeable Ca} + \text{Mg} + \text{K} + \text{Na} + \text{Al}) \qquad (2)$$

The sodium adsorption ratio (SAR) is used when describing the sodicity of applied water or the soil solution. It is defined as:

$$\text{SAR} = [\text{Na}^{+}] / ([\text{Ca}^{2+} + \text{Mg}^{2+}]/2)^{1/2} \qquad (3)$$

where [ ] refers to concentration in $\text{mmol}_c\ \text{L}^{-1}$. Another parameter commonly used is the total cation concentration (TCC) of a solution which can be either directly measured or approximated by:

$$\text{TCC} (\text{mmol}_c\ \text{L}^{-1}) \approx \text{electrical conductivity} (\text{dS m}^{-1}) * 10 \qquad (4)$$

The quantitative sodicity criterion proposed by Northcote and Skene (1972) has been widely used in Australia and defines "non-sodic" soils as those soils with an exchangeable sodium percentage of <6 in the top metre of the soil profile. Soils with an ESP of 6-14 are categorised as "sodic" and soils with an ESP ≥15 as "strongly sodic". However, it should be noted that these critical levels are arbitrarily defined and that the effect of sodium on aggregate stability and dispersion is a continuous function down to zero (Sumner 1993).

The influence of sodicity on soil physical properties also varies with clay content and clay mineralogy (Shaw and Thorburn, 1985). In higher clay soils, lower ESP levels have a more significant effect. Similarly, for surface soils unprotected by vegetative cover/mulch (and therefore subject to rainfall energy) or soils exposed to repeated machinery disturbance an ESP value of 3 or less may be more appropriately used to identify problem soils. Hence, Sumner (1993) concludes that the term "sodic" is compromised, and that the set of properties associated with these soils (eg. dispersion) should be substituted since they are less ambiguous. In the case of road construction and disturbed land management, it is more appropriate to refer to this group of problem soils by the more broadly inclusive term of "dispersive soils".

Distribution of Sodic Soils in Queensland

Based on the Northcote and Skene (1972) categories outlined above, approximately 25% of the soils in Queensland (Figure 1) are regarded as strongly sodic and another 20% are variably sodic (Shaw *et al.*, 1994). While sodic soils are commonly associated with the weathering of sedimentary parent materials of marine origin, sodium accessions to soils can also occur via rainfall, groundwater rise, or from aeolian sources. No distinguishing trend in the incidence of sodic soils with parent material has been found in Queensland, except for a reduced incidence of strongly sodic soils on calcic geologies (Shaw *et al*., 1994). However, ESP has been found (Powell *et al*. 1995) to increase with depth for a range of Queensland soils (Figure 2). The age of alluvial sediments has also been found to be important as older sediments are more likely to accumulate higher proportions of sodium and magnesium (Walker and Coventry, 1976). Similarly, topographic location is important in the development of sodic soils with locations associated with the accumulation of soluble salts transported by shallow groundwater seepage more likely to be sodic. There are also strong associations commonly found between the nature of the vegetation and soils at a site. For example, Webb *et al.* (1982) found that *Eucalyptus camageana* (Dawson Gum) communities on duplex soils indicated the presence of strongly sodic material at a depth of 0.6 m.

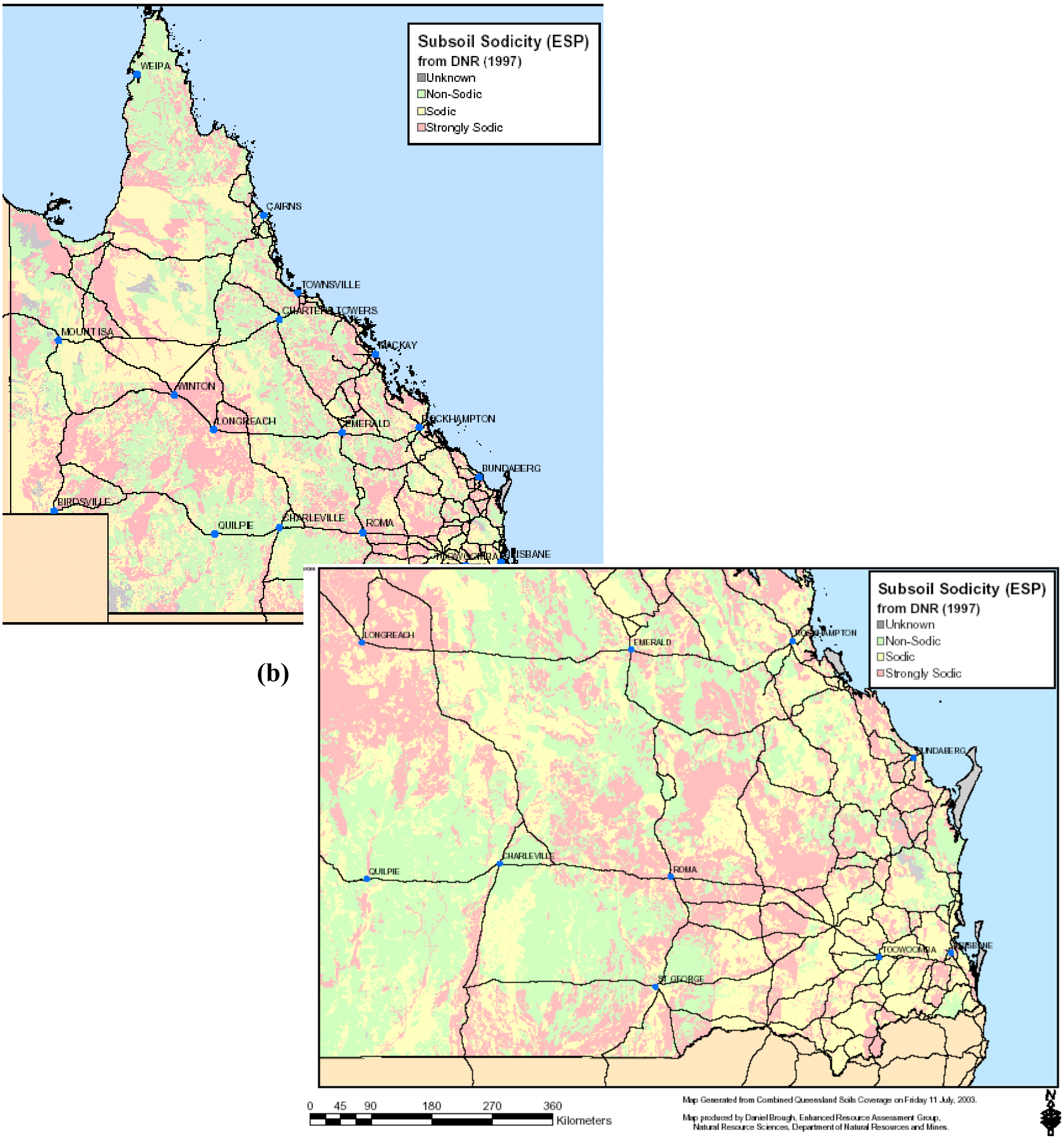

Figure 1. Distribution of sodic soils in (a) Queensland and (b) south-east Queensland
(*DNRM, 2003*)

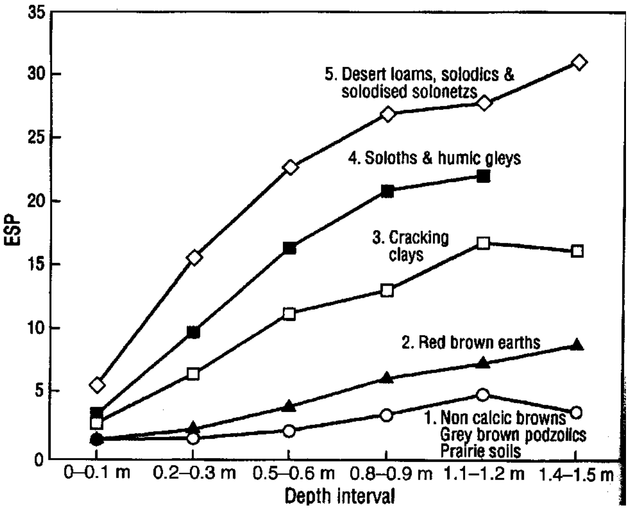

Figure 2. *Mean ESP values with increasing depth for Queensland soils* (from Powell *et al.*, 1995)

Dispersive Soil Processes

At sub-micron scales, clay mineral crystal layers in soils are closely associated with each other to form structures known as "domains" or "tactoids" (Quirk 2001). In such systems, dispersion can only occur if the individual mineral layers separate. Quirk (2001) described this system using a simple "three plate model" in which individual clay crystals overlap to a certain extent, and slit-shaped pores form within the domain or tactoid where crystals do not overlap (see Figure 3).

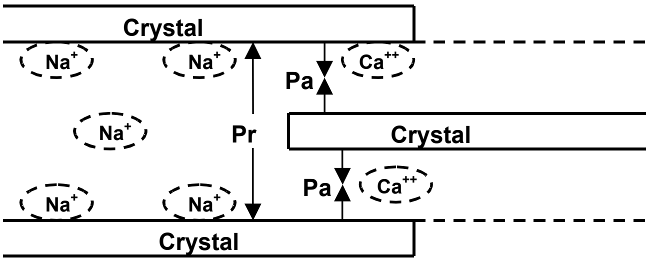

Figure 3. *A simple 3-plane model to describe the arrangement of clay crystals in a clay domain* (from Quirk 2001)

This model is useful for illustrating the dispersion process and the effect of exchangeable sodium on dispersion. When water or an electrolyte solution is added to a soil, repulsive pressures (Pr), associated with osmotic effects and the change in the diffuse double layer, develop over the surface area of the larger slit-shaped pores, while an attractive pressure (Pa) associated with van der Waals forces operates over the surface area of the closely-aligned crystals. Dispersive cations such as sodium tend to concentrate in the slit-shaped pores (Sumner 1993), and form extensive double layers (compared to smaller double layers for cations of higher valence), particularly if the salt concentration of the soil solution is low. Thus, the repulsive force can more readily exceed the attractive force in soil systems containing sodium, resulting in "spontaneous dispersion" when the soil is exposed to excess water at a low electrolyte concentration. When the repulsive force is nearly as large as the attractive force, dispersion will require the input of a threshold shear stress from flowing water or raindrops (Sherard *et al.*, 1976).

In soils, most of the focus has been on the effect of ESP and electrolyte concentration (EC) on excessive swelling and dispersion, and on the subsequent effects on hydraulic conductivity and crust formation on drying. Quirk and Schofield (1955) and many others since that time (Quirk 2001) have used plots of ESP against electrolyte concentration to define regions of stable *versus* reducing hydraulic conductivity or soil flocculation *versus* deflocculation/dispersion. They investigated the permeability of a soil to solutions of different SAR and EC. The soil was first equilibrated with concentrated solutions at a range of SARs. For each SAR, the EC of the solution was then decreased (while maintaining a constant SAR and thus maintaining a constant soil ESP) until reductions in permeability and dispersed clay in the percolate were observed. On the basis of these findings, three threshold electrolyte concentrations have been defined:

Threshold concentration – "the salt concentration for a given solution SAR at which the permeability was decreased by 15%", presumably due to excess swelling.

Turbidity concentration - "the salt concentration for a given solution SAR at which the dismantling of soil microstructure is indicated by the appearance of dispersed particles in the percolate".

Flocculation concentration - "the salt concentration for a given solution SAR at which a dispersed soil suspension will flocculate".

Quirk and Schofield (1955) found that the "turbidity concentration" is approximately 25% of the "threshold concentration", and about 12% of the "flocculation concentration". This shows that dispersion and flocculation are not reversible, and that flocculation tests cannot be used to predict dispersion. An illustrative version of an ESP-EC diagram is shown in Figure 4. The diagram shows threshold concentrations for both permeability and clay dispersion. The actual threshold values will depend on a number of factors including clay mineral type, organic matter content, other cations present, and input of mechanical energy (Sumner 1993).

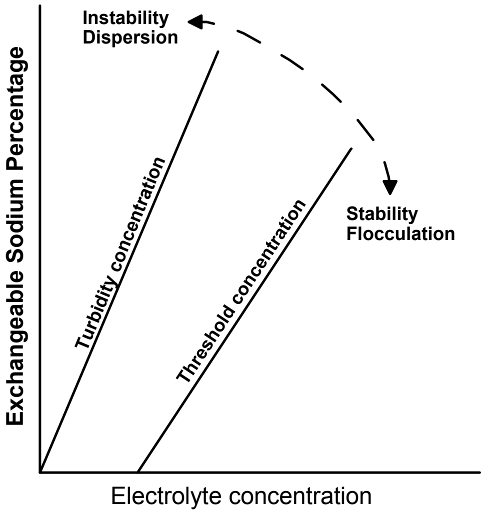

Figure 4. *Soil ESP versus electrolyte concentration of the equilibrium solution, showing threshold curves for decreased permeability and clay dispersion*
(Note: points anti-clockwise from the threshold lines represent instability: points clockwise from the threshold lines represent stability)

Identifying Dispersive Soils

Dispersion tests are useful for identifying problem soils (particularly, those susceptible to tunnelling) The three main types of dispersion test are:

- Emerson test (AS 1289.3.8.1 – 1997)
- Pinhole test (AS 1289.3.8.3 – 1997)
- Dispersion Index test

The Emerson test (eg. Mackenzie *et al.,* 2002) is a quick and simple test that can be used to assist in the rapid identification of problem soils. It initially measures both slaking and spontaneous dispersion of an air-dry soil aggregate immersed in deionised water (Figure 5). If spontaneous dispersion is "slight to nil", the soil is remoulded at near maximum field water content, and dispersion is again observed. Finally, if soil does not disperse after remoulding, the soil is shaken in water. However, care needs to be taken in the selection of aggregates for the Emerson test to ensure they are representative of the soil, particularly for mottled soils (Murphy, 1995).

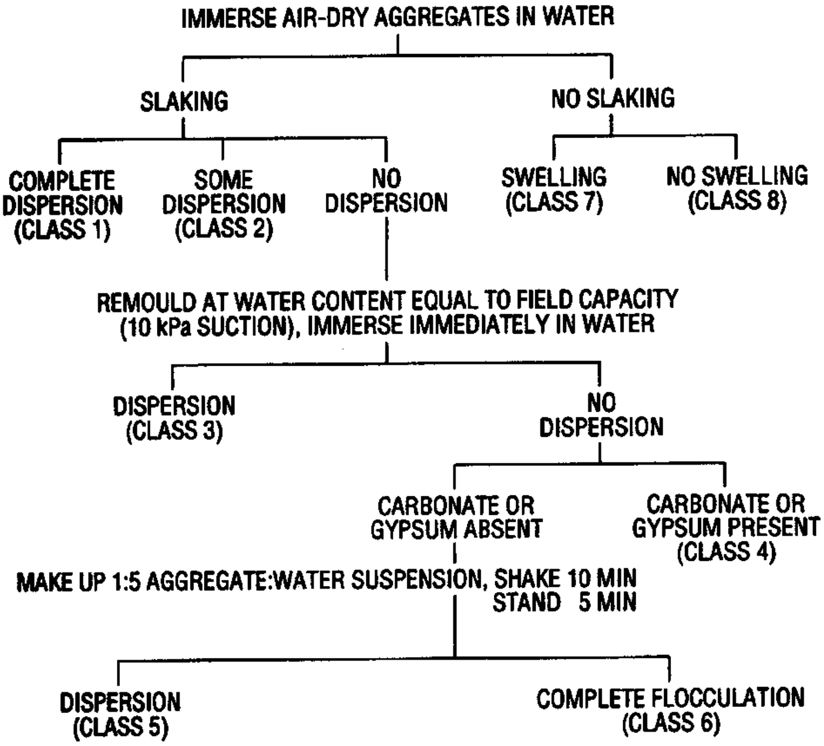

Figure 5. *Framework for determining the Emerson aggregate stability class* (from Murphy, 1995)

In the Pinhole test, mechanical energy is applied via water flow through a small hole (pinhole 1.07 mm diameter, Schafer 1978) placed in a compacted soil specimen. Distilled water is passed through the pinhole, with an initial mean velocity 0.4 to 0.8 m s^{-1}, and measurements are taken of the water turbidity and flow rates exiting the pinhole. Visual inspection of the pinhole is carried out after testing is complete (Schafer, 1978). The Pinhole test is specifically designed to identify dispersive soils susceptible to tunnelling. Dispersive clay soils produce turbid water with a rapidly eroding hole, whereas non-dispersive clay soils result in clear water at the outlet and little change in pinhole size (Sherard *et al.,* 1976).

The Dispersion Index test has been widely used in Australia for the detection of problem soils. This test applies mechanical energy through an end-over end shaking technique. Soil is shaken in distilled water for 2 hrs, and the % particles < 2 micron (A) is measured. This % is compared with the % particles < 2 micron (B) measured after the soil has been shaken with dispersant, and clay dispersion is considered complete. The Dispersion Index is calculated as the ratio (B/A). Ritchie (1965) classified soils with DI<3 as "susceptible to tunnelling". This classification is the same as that used by the Soil Conservation Service in the USA. They used a Dispersion Ratio, calculated as (A/B), and set a threshold value of DR at > 0.33. Ritchie's (1965) classification was confirmed by further field studies (Charman, 1969). All soil layers that showed tunnelling in the field had a DI<3. However, not all soils with DI<3 exhibited tunnelling, suggesting that a range of climatic and site factors, in addition to soil dispersion, are involved in tunnel initiation.

Field Problems Associated with Dispersive Soils

A wide range of both structural and biological problems are manifested by dispersion of unstable soils under field conditions (Figure 6). All of these problems have the potential to impact on the operating and maintenance costs associated with structures constructed with these materials.

Rapid wetting of unstable soils results in slaking. Where the ESP is high and the electrolyte concentration is low, spontaneous swelling and dispersion will also occur. Even where the electrolyte concentration is above the threshold concentration for spontaneous dispersion, the application of energy to the soil via raindrop impact, turbulent water flow, or machinery action can be sufficient to produce dispersed clay material. Under any of these conditions, a "washed in layer" forms on the soil surface producing a surface seal and subsequent crusting. This layer can act to reduce infiltration (eg. Figure 7), increase run-off, inhibit gaseous flows into the soil and impede seedling establishment.

While the surface erosion, soil structural and revegetation problems associated with dispersive soils are problematic, these problems have the advantage of being able to be visually assessed and where appropriate, rapidly addressed. However, problems associated with subsoil structural decline and tunnelling are often less commonly identified and may take longer to manifest. Where low electrolyte concentrations exist within the profile, dispersion and structural decline reduce available water capacities and create conditions (eg. extreme hardness when dry, poor internal drainage when wet) which inhibit root growth. Where water is moving through the profile, dispersed clay can be translocated, resulting in tunnelling, surface subsidence, collapse of road cuttings, foundation failure and increased erosion.

Crouch *et al.* (1986) briefly reviewed the occurrence of tunnelling on a worldwide scale. Tunnelling has been observed in all climates, with wide variations in temperature, rainfall and seasonality of rainfall. There is also a wide variety of soil types, ranging across duplex/texture contrast, silty loess and uniform heavy clay soils. Clay type does not appear to be an important variable, with tunnelling occurring in soils containing both montmorillonite (highly expansive) and kaolinite clays.

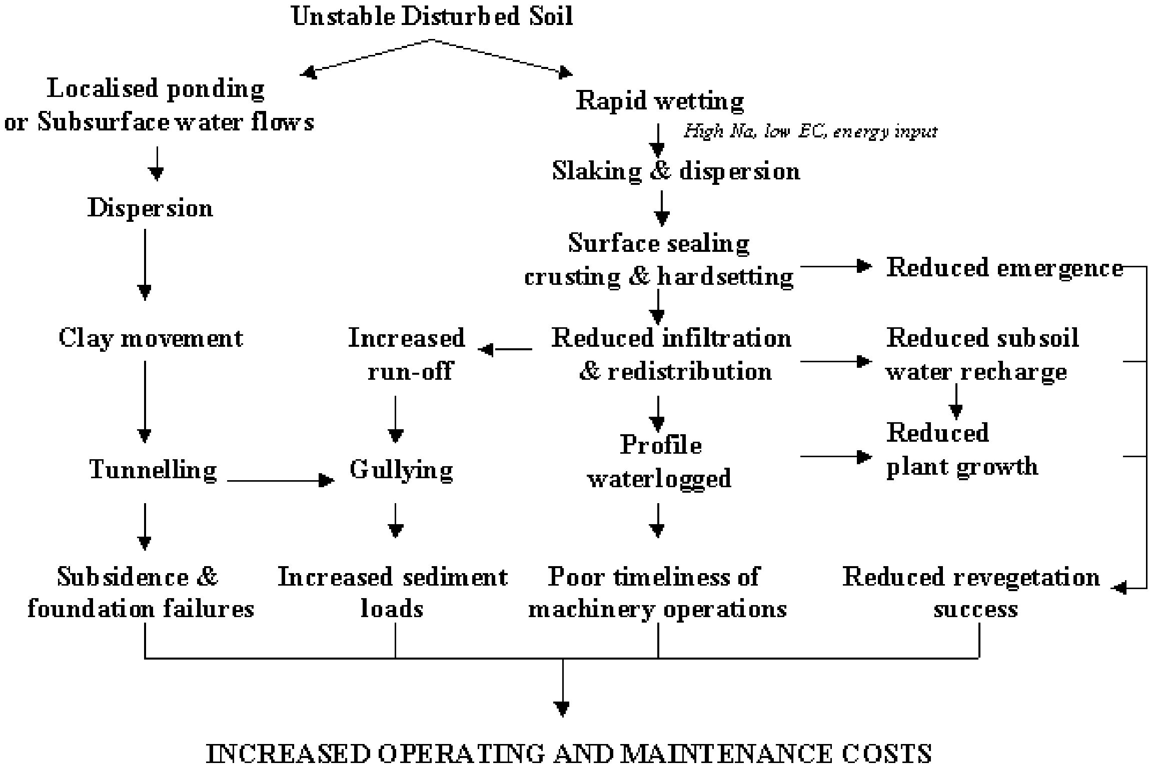

Figure 6. *Conceptual model showing the mechanisms by which dispersion may affect soil physical properties, construction and revegetation activities* (adapted from So and Aylmore, 1993)

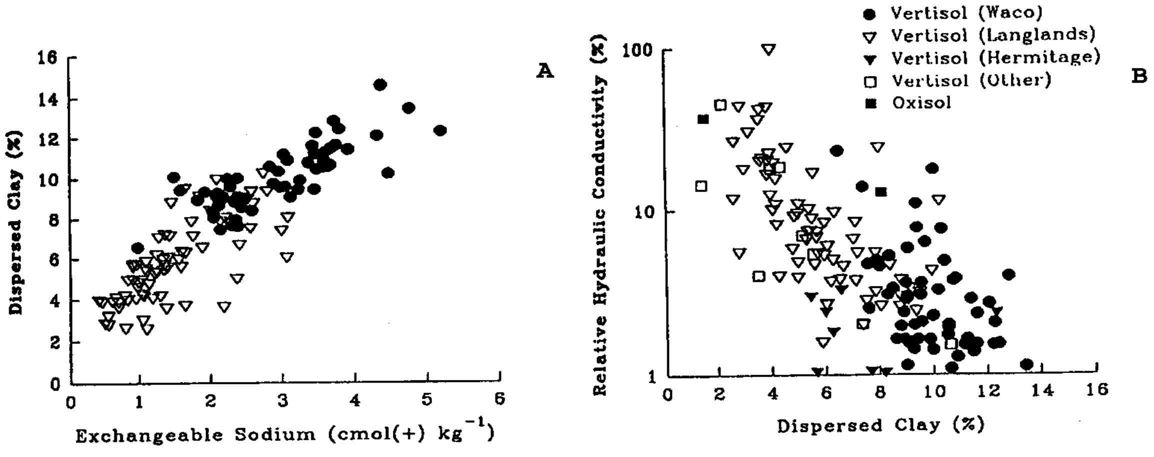

Figure 7. *Relationship between (A) exchangeable sodium and dispersed clay and (B) dispersed clay and the hydraulic conductivity for Australian vertisols and oxisols* (from So and Cook, 1993)

As a result of the wide variations in soil and climatic conditions under which tunnelling has been found, different reasons are given for tunnel formation. In general, tunnels are associated with less permeable soils, and in particular those with an impermeable layer. In such soils, a perched water table may form above the impermeable layer. However, there are reports of tunnelling in permeable soils, associated with zones of very high permeability. The unifying concept in this case appears to be spatial variability in permeability within the soil profile**.** This results in preferential flow paths, allowing flow concentrations that increase the erosion/dispersion levels.

For tunnelling to occur, Rosewell (1970) concludes that two conditions must be met. Firstly, the soil must disperse into the water flowing through the soil; and secondly, the soil permeability must be great enough to ensure that any dispersed clay will pass through the soil without causing a blockage. On this basis, Figure 8 identifies three potential situations:

- Situation A: ESP-EC of the material in the “Dispersion” or “reduced permeability” zones, rapid wetting.
- Situation B: ESP-EC of the material in the “Flocculation, high permeability” zone, rapid wetting.
- Situation C: ESP-EC of the material in the “Flocculation, high permeability” zone, slow wetting.

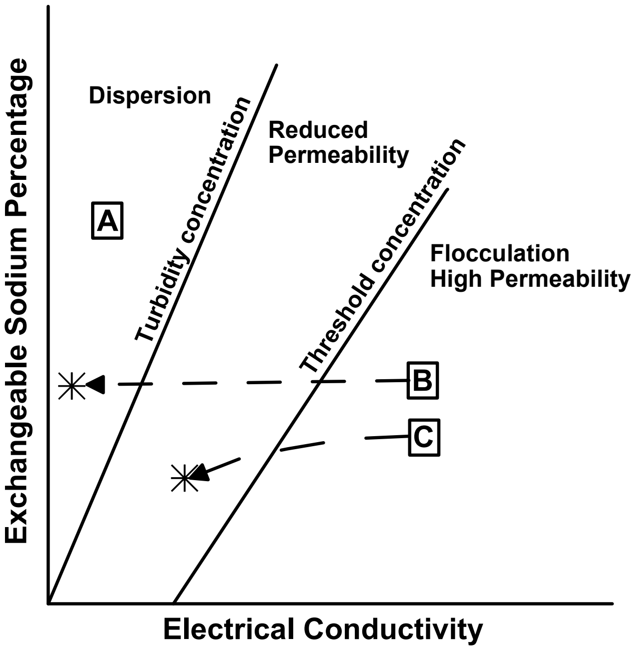

Figure 8. *Changes in EC and ESP for different types of soil material and wetting conditions when water containing low levels of salt is added*
(paths for situations B and C join the square box and the asterisk)

According to Wood *et al.* (quoted by Rosewell, 1970), tunnelling will occur in situation A if the permeability of the material is greater than about 4 mm/hr. If the permeability is less than this value, the spontaneously dispersed clay will be trapped as a “gel” structure within the soil pores. For situations B and C, the probability of tunnelling depends also on the rate of wetting of the material, and the chances that the soil will become dispersive. When water permeates through material with relatively high EC, salt is leached out. If wetting is rapid, EC will be reduced as shown for situation B (Figure 8), and the soil will enter the “dispersion” zone. This explains the failure of earth dams when they are rapidly filled by rainfall runoff.

In situation C, if wetting and reduction in EC is slow, ESP will also reduce slowly as the soil equilibrates with the flowing water. More importantly, if the soil crosses the "threshold concentration" permeability will be decreased and salt leaching may stop. In this situation, the soil may never enter the "dispersion" zone, and tunnelling will not occur. In this situation, swelling and dispersive clays may inhibit tunnelling due to restrictions in pore spacing caused by swelling of the soil structure. If the rate of swelling exceeds the rate of dispersive erosion through small tunnels, the flow path is cut off, preventing further erosion. If the rate of swelling is slower than the removal of clay through the generating tunnels, the tunnel system can progress and may be exacerbated by the restriction in other areas of the soil mass diverting flow to the developing tunnel spacing.

Managing Dispersive Soils

The use of dispersive materials on construction and revegetation sites should be avoided wherever possible. Where it is not cost effective to avoid exposure and usage of dispersive materials, a range of management options are available. These include burying materials beneath a stable soil cover, managing water flows over and through the dispersive material and treating exposed material with amendments. The most viable and cost effective management option will depend on the site conditions and material properties. In some cases, it may be necessary to implement a combination of strategies to effectively manage the site.

Topsoiling dispersive materials

Where possible, dispersive soils should be buried with a topsoil cover to reduce problems associated with sealing, crusting, and erosion, and to enhance vegetative establishment. Potentially dispersive soil exposed to raindrop energy or subjected to other mechanical energy (eg. machinery movement, turbulent water flows) will also produce elevated suspended sediment loads. Topsoil covers can also play a significant role in reducing the potential for tunnel formation where they are sufficiently deep to store infiltrated rainfall and ponded water above the dispersed material. In these cases, the minimum depth of the topsoil cover will be a function of the climatic conditions (especially rainfall patterns and evaporation potential), the topsoil texture and structure (ie. plant available water stored) and the evapo-transpiration demand of the vegetation being established. In general, deeper topsoil covers should be used in areas with high rainfall, cool temperatures, or where lighter textured soils are used for the cover.

Managing water flows

The management of water flows over and through dispersive materials is a key tool in the management of these dispersive soils. Strategies include (a) the diversion of water flows away from these materials, (b) minimising the potential for convergence and/or ponding of surface flows and (c) compacting to minimise water movement through the material. Where spontaneously dispersive soils are exposed to surface water flows, clay particles will be rapidly suspended producing high clay loads in run-off water. The use of concave batter slopes without benching or contour banks has been shown to reduce the potential for convergence of water flows and to minimise flow velocities leading to gullying.

Where comparatively low EC water is allowed to move through potentially dispersive soils, the leaching of salts out of the profile may produce spontaneous dispersion leading to the formation of tunnels. Hence, Hosking (1967, quoted by Crouch, 1976) concluded that the only practical way of preventing tunnel development is to divert water away from the catchment areas of the tunnels. In a similar vein, Floyd (1974) recommends that, if an area of non-susceptible soils occurs upslope of a dispersive material, banks and gully control structures should be built on the stable soil to divert water safely away from the dispersible material. Floyd specifically recommends that "care should be taken not to build extensive bank systems, especially level absorption banks, on dispersive soils" due to the potential for both surface erosion and tunnel formation.

It is also important to minimise water movement through potentially dispersive material to minimise the risk of leaching salt out of the profile and reducing the EC of the material to below the TCC. Where subsurface water movement is likely to occur through potentially dispersive fill material, one option is to install interception drains to reduce the volume of water moving through the fill. To protect potentially dispersive soils under roadways, interception trenches may be excavated on both sides of the road (ie. parallel to the road) and upslope of where the natural land surface becomes 0.5 m lower than the surface of the road (so that the base of the trench is 1.5-2.0 m below the road surface). Trenches observed to carry large quantities of flow should have agricultural drainage pipe installed, and be backfilled with an appropriate porous material. Trenches not observed to carry large quantities of flow may be backfilled with a porous material. Care should be taken to ensure that agricultural drainage pipe and trenches do not discharge directly onto the fill embankments.

Soil pore size influences the rate of water movement (soil permeability) through the soil structure (Rosewell, 1970). Dispersive soils need a volume of pore space around clay particles to allow water contact with the dispersive clay components, continuity of pore spaces to allow mechanical dispersion to remove dispersed material and allow cleaner water to enter allowing further dispersion. Reducing the porosity of the soil and the continuity of pore spaces reduces the potential for dispersion to occur and reduces the rate at which water can remove dispersed material from the soil profile. High permeability (due to factors such as low density, resulting from poor soil compaction in structures) will encourage leaching of salts from the profile, thereby reducing the EC and increasing the potential for dispersion. High permeability will also allow movement of dispersed clay through the soil and enhance erosion rates of dispersed material from the soil matrix. Increasing compaction levels reduces the soil permeability and restricts the movement of water and dispersed clay through the soil body, decreasing the severity of dispersion in the soil and restricting tunnel formation.

Ritchie (1965) studied the effect of compaction on tunnelling failure of farm dams. Materials were compacted to dry densities of 0.8-1.5 t/m^3, and 100% dam failure was noted at a density of 0.8 t/m^3. For dam walls of dispersive material, research by the NSW Dept Land and Water Conservation (Rosewell, 1970) showed that compaction to at least 85% of the Proctor maximum dry density was essential to prevent tunnelling. This represented a dry density of about 1.5 t/m^3. This is beyond the compaction capacity of a crawler tractor. For non-dispersive materials compaction to 70-75% of Proctor maximum should be sufficient, and this is readily obtained using conventional earthwork construction techniques.

A non-compacted dispersive layer above an impermeable layer is particularly susceptible to tunnel erosion since positive hydraulic pressures can build up in this layer (Crouch 1976). An example, is a trench dug for pipe/cable installation constructed through a dispersive material. In this case, fill around the pipe/cable should be compacted to at least the density of the surrounding material and the soil surface of the filled trench left slightly higher than the surrounding land to minimise subsequent surface water ponding, infiltration and leaching within the trench and around the pipe/cable.

Use of amendments

Gypsum ($CaSO_4.2H_2O$) has been widely used as a calcium source to replace sodium on the soil exchange complex. The application of gypsum to soils will both increase the soil solution electrolyte concentration and the exchangeable calcium levels in the soil. Both of these actions reduce the inter-particle swelling pressures and the potential for dispersion. Surface applied gypsum generally increases infiltration rates and reduces dispersion but the process is sometimes slow because the gypsum distributes slowly into the soil (Sharma, 1971). Mixing the gypsum into the soil surface layers accelerates the reclamation process because the calcium is physically placed where it will react. Because leaching removes gypsum from the upper part of the soil profile where the major problems of dispersion and hardsetting are located, periodic applications are necessary to both maintain adequate electrolyte to prevent dispersion and slumping and to slowly reduce the ESP level (Chartres *et al.*, 1985; Greene and Ford, 1985).

Long chain polyacrylamides have been shown to increase aggregate stability, reducing dispersion and maintaining infiltration rates on dispersive soils (eg. Levy *et al.*, 1992). However, the effect is highly variable between the various polyacrylamides and the properties (especially texture) of the dispersive soil. The benefit of polyacrylamide additions is also generally short term due to their rapid degradation, suggesting that these amendments will only be useful in applications requiring temporary protection (Vacher *et al.* in press). Both gypsum and polyacrylamides have also been shown to work effectively as flocculants to reduce suspended sediment loads in run-off waters.

Surface applications of organic mulches are generally observed to improve the revegetation success and reduce erosion from dispersive soils. While components of various organic materials have been shown to have both positive (eg. Emerson *et al.*, 1986; Rengasamy and Olsson, 1991) and negative (eg. Gupta *et al.*, 1984) effects on dispersion induced by sodium, the main effect of organic mulches is the protection of the soil surface from rainfall impact energies, and the increased surface detention of incident rainfall. Organic mulches also provide a protective cover which reduces daytime surface temperatures and the rate of soil surface drying. Hence, under hot, dry conditions organic mulches reduce the rate of surface crust formation enabling better vegetation establishment.

Conclusions

Sodic soils cover approximately 45% of the Queensland land area. However, not all sodic soils are dispersive and not all dispersive soils are sodic. Dispersive soils are problematic for road construction and maintenance activities and should be identified so that their constraints can be addressed in project planning. Where possible, dispersive soils should be avoided in construction activities as they are susceptible to erosion, structural decline and tunnelling, leading to difficulties with revegetation, sediment management and higher maintenance costs. However, where dispersive soils are used, a range of construction and management options are available to minimise impacts and reduce on-going operating and maintenance costs.

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