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Minimising Water Losses in Agriculture through the Application of Impact Rollers

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Summary Due to recent water restrictions in the rice and cotton industries, minimising water loss has become an important issue. Water loss from storages and canal structures, along with infiltration in the irrigation areas is significant. The impact roller is often used to reduce water loss through percolation and infiltration by increasing the soil density. In the past there has been a lack of analysis and controlled testing of compacted areas resulting in a shortage of information to assist in formulating rational specifications for agricultural applications of impact rollers. In this paper, testing of permeability and shear strength of soil in a cotton growing area in western NSW, before, during and after the application of an impact roller are presented. Guidelines have been developed for the selection of suitable agricultural applications for the impact roller and recommendations made on soil testing before, during and after construction.

1. INTRODUCTION

Management of water is a major problem facing Australia as the next century approaches. The largest single users of water are the agricultural industries. Inadequate quantity and quality of water is already impacting severely on the industry in many areas. Yet, of each litre of water diverted from rivers and groundwater systems, a high proportion is lost or wasted as:

- evaporation;
- run-off;
- seepage from water management structures;
- percolation below the root-zone.

Good management of water resources demands the minimisation of these sources of loss not only to reduce wastage of water, but to reduce the associated environmental damage through contamination of water supplies with salts and nutrients. Geotechnical engineering may be able to contribute little to reduction of losses due to evaporation and run-off. There is however, considerable scope for the geotechnical engineer in management of seepage losses and percolation.

The Impact Roller has only been available outside South Africa for less than 15 years. Its use in Australia in mining and civil engineering has mainly been intended to achieve compaction to increase the strength and stability and to reduce compressibility of soils. Even in the engineering literature there is little published data available for the guidance of engineers in its use for these purposes. There has been little investigation of its effects on permeability.

The Impact Roller has now found applications in agriculture, particularly in rice and cotton growing. However to date these applications have been guided by intuition and pragmatism. There has been little or no hard data available for guidance on the applicability and appropriate methodology to apply to particular projects.

The aims of the study are: to review the use of soil compaction in minimising water losses; to review the operation of impact rollers; to present the results of a field study into the effectiveness of impact rollers in agriculture, including permeability, shear strength and settlement; and from this to develop guidelines for the use of impact rollers in agriculture.

2. BACKGROUND

Cotton growing relies heavily on irrigation to ensure reliable yields, essential for survival in this competitive industry. As in much of Australia's irrigation infrastructure, water is transported in canals and stored on-farm in large dams. Many of these leak, due to poor compaction of the embankments and floors of storages and canals. Often this may be due to insufficient attention to soil characteristics or compaction during construction. After construction, permeability of the soil mass may be increased many-fold by burrowing activities (e.g. earthworms and crustaceans), or by growth and decay of roots. Many of these effects may be reduced by the compaction of embankments and floors of the water transport and storage structures.

Dowling (1994) describes some causes of water loss in storages, in particular deep cracks, holes due to weed roots and earthworms, and storages with areas of high permeability soils. In one case, three times as much water was being lost compared to normal, amounting to four megalitres a day from a 20 hectare storage (Dowling, 1994).

Rice is grown in paddies, which are fields submerged to a shallow depth for the major part of the growing cycle. In 1985, concerns about the amount of water percolating into the groundwater resulted in restrictions for rice paddock water use being introduced, which is now limited to 16 ML/ha (Humphreys, Meyer, Prathapar & Smith, 1994). After extensive analysis, Humphreys *et al.* (1994) concluded that up to 3-4 ML/ha was being lost through deep percolation. They similarly concluded that rice growing was a major contributor to the rise in watertables and increasing salinisation problems in areas of southern New South Wales. To reduce these problems, the amount of deep percolation must be reduced. Sharma, Ingram and Harnpichitvitaya (1995) suggest that subsoil compaction is the most appropriate method of reducing percolation.

2.1 Effect of compaction on permeability.

When soil is compacted, the solid particles are rearranged with a resultant reduction in the sizes of the voids between the particles. Since it is through these voids that water must pass, this reduces the permeability of the soil to water, even where conduits formed in the soil (such as animal burrows or root holes) contribute significantly to the permeability. Effective compaction can result in the collapse of these pathways to significantly reduce permeability.

Compaction of the soils within the crop root-zone is undesirable. For crops such as rice, the ideal compaction tool will have its main effect at some depth, but little effect nearer the surface.

2.2 The Impact Roller

The Impact Roller was introduced to Australia from South Africa by Broons Hire (SA) in the mid 1980's. This technique has found extensive use in civil engineering and mining roles as a tool able to achieve compaction to significant depths in in-situ materials or in materials placed in deep layers. One of the characteristics of this equipment is that whilst it can achieve significant compaction at depths (depending on soil type and conditions) up to 1-2 m or more, the effect on the upper 0.2 m is less.

When using alternative compaction equipment, the thickness of compaction layers obtainable has traditionally been 0.15 m. The impact roller technology has increased this thickness to 0.5 m (Van der Merwe, 1985). Despite this, the depth of effective compaction obtained by the impact roller is still dependant on the material to be compacted.

Over the past few years it has found applications in the cotton industry, where it has mainly been used to improve existing water storages, channels and embankments. More recently, it has been used in the rice industry to compact clay soils beneath rice paddies. Here the lesser compaction at shallow depth inherent in such equipment may be a distinct advantage.

3. METHODOLOGY

In an attempt to provide a basis for the assessment and use of this compaction technology, a study has been made of the effects of compaction using the Broons Hire BH-1300 impact roller on existing irrigation channel embankments at Lake Tandou in western New South Wales. The BH-1300 impact roller is essentially a four sided roller weighing 7900 kg which is towed by an appropriate tractor. The roller is 1.3 m wide and is supported by a roller frame.

During the recompaction of these embankments by Broons, measurements were taken by the author on two embankments at depths between 0.25 m and 0.75 m after varying numbers of passes of the roller. These measurements included:

- permeability in-situ using a Guelph Permeameter (Guelph Permeameter, 1987);
- penetration resistance (ASAE S313.2 1988);
- particle size distribution (AS 1289 3.6.3 - 1994) and Atterberg limits (AS 1289 3.2.1 - 1995, AS 1289 3.1.1 - 1995);
- settlement in-situ over a 3.0 m by embankment width grid using a Wild auto-level;
- moisture content in-situ (AS 1289 2.1.1 - 1992);
- standard compaction test (AS 1289 5.1.1 - 1993).

4. RESULTS AND DISCUSSION

4.1 Test Sites

Field trials were undertaken on the western edge of Tandou Cotton on Lake Tandou in western New South Wales. Two embankments (A and B) with similar soil characteristics and known seepage problems were chosen.

Both embankments were constructed at the same time during the late 1970's. However, due to recent work on embankment B to increase its height, the crest width of the two differed. Dimensions of the two embankments were:

- Embankment A: 3.4m crest width; 1.59m height; approximate 2:1 batter;
- Embankment B: 4.4m crest width; 1.58m height; approximate 2:1 batter.

Recent work on embankment B consisted of the addition of approximately 0.5m of compacted soil to the crest of the embankment. Compaction resulted from earthmoving equipment manoeuvring on the embankment. To allow vehicle access, embankments served as roads, further compacting the embankments.

Water levels in the associated channels were reduced at different times in association with the crop irrigation requirements. Water levels in the channel enclosed by embankment A had been reduced several weeks before the application of the impact roller, while embankment B water levels had been reduced only a week before the application.

4.2 Soil Characteristics

Soil throughout the embankment profile has been classified as a CH soil (Unified Classification System) with a particle size distribution described in Figure 1. Other soil characteristics are outlined in Table 1. Table 2 details results showing embankment B had higher moisture contents compared to embankment A due to different timing of the reduction of channel water levels already outlined.

4.3 Moisture Content

Several papers describe the wide range of soil moisture contents in which the impact roller can be successfully used. Broons Hire (1994) suggests the most efficient moisture content is 2% below the laboratory modified optimum. However, Chester (1994) states that in one case the required compaction was achieved when the moisture content was between 2.5 and 4.5% below the optimum moisture content. While Coffey Partners International Pty Ltd (1997, Appendix B) determined that the required compaction could be obtained up to 7.5% above the optimum moisture content.

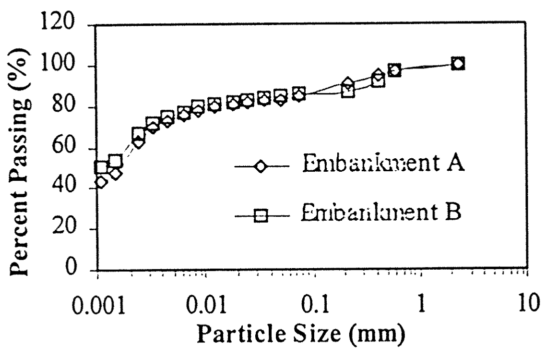

Figure 1. Particle size distribution.

The optimum moisture contents for both embankments at testing depths are within the acceptable limits previously outlined, and consequently should provide an acceptable environment for the successful use of an impact roller.

Table 1. Results from optimum moisture content (OMC), maximum dry density (MDD), liquid limit (w_L) and plasticity index (I_p) using standard compaction tests on soils of embankments A and B.

Test	Embankment A	Embankment B
OMC %	25.7	25.2
MDD (kg/m^3)	1420	1430
w_L %	54.2	53.2
I_p %	27.2	27.4

Table 2. Initial moisture contents at the centre of the embankment.

Depth	Initial Moisture Content (%)	
(m)	Embankment A	Embankment B
0 - 0.25	8.3	9.3
0.25 - 0.50	10.2	21.2
0.50 - 0.75	26.1	28.3

4.4 Permeability

During field trials aimed at determining the effectiveness of the impact roller in reducing the permeability of embankments, in-situ permeability tests were undertaken at several depths on the two embankments. Results shown in Figure 2 indicate that after fifteen roller passes, the hydraulic conductivity was reduced to an unmeasurably low value below 0.25 m at the centre of the embankment. These results also suggested that during the compaction process the soil structure within the top 0.5m profile was periodically shattered by the roller, thus temporarily increasing the hydraulic conductivity (see after 10 passes at 0.25 and 0.5m depth, Figure 2). In all trials, an increased hydraulic conductivity consistent with shattering was detected after ten passes reflecting a potential problem with the impact roller technology.

Current guidelines obtained from the impact roller suppliers fail to recognise the shattering problem in agricultural applications, including channel rectification works. Despite this, current recommendations for channel rectification suggest that the number of roller passes in this study is sufficient to minimise the risk of shattering, although there is a potential for ineffective compaction if the recommended number of passes are not adhered to. Further studies are required in order to minimise the risk of increased hydraulic conductivity through shattered soils.

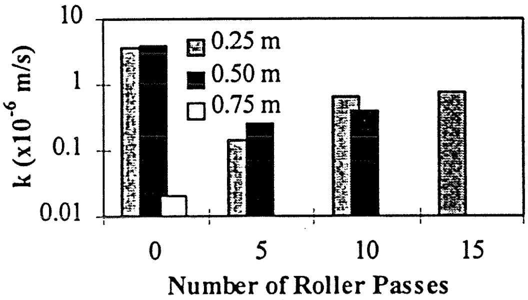

Figure 2. Hydraulic conductivity (k) at various depths after 5, 10 and 15 passes of the roller at the centre of embankment A.

Unlike embankment A, embankment B had indeterminable initial hydraulic conductivities below 0.25m, suggesting seepage was not occurring through the embankment. Since seepage problems were evident due to the accumulation of minerals at the base of the embankment and hydraulic conductivity throughout the embankment was small, the question should be raised as to where the seepage was occurring.

Although compaction on the embankment crest should reduce the seepage through the embankment, if seepage occurred under the embankment, this form of roller application would have a negligible effect. Thus, during channel rectification, compaction should be considered to reduce the infiltration and percolation through the channel floor. The optimal solution to channel seepage, however should be the compaction of channels, embankment bases, and embankments during the construction process.

As Boussinesq's elastic theory describes (Clifford and Bowes, n.d.) there is lateral distribution of stress under the impact roller and under wheels. Thus it is not necessary to roll the entire surface or overlap adjacent passes to obtain satisfactory compaction. Data obtained during field trials supports this theory to an extent.

Hydraulic conductivity was measured at the edge of the roller mass and the edge of the embankment (shown in Figures 3 and 4 respectively). At the edge of the embankment, the effects of lateral dissipation were less apparent in comparison to the centre. Embankment A showed a reduction in the hydraulic conductivity at all depths (Figures 2, 3, and 4). In contrast embankment B showed an increase in hydraulic conductivity at the embankment edges (Figure 4). This suggests cracks developed at the edges of the embankment resulting from the high moisture content causing a kneading action throughout the embankment. Alternatively, cracking could be related to the wider crest of embankment B. Although the compaction process aims to create an impermeable embankment core, the inclusions of crack the embankment edges should be seen as undesirable.

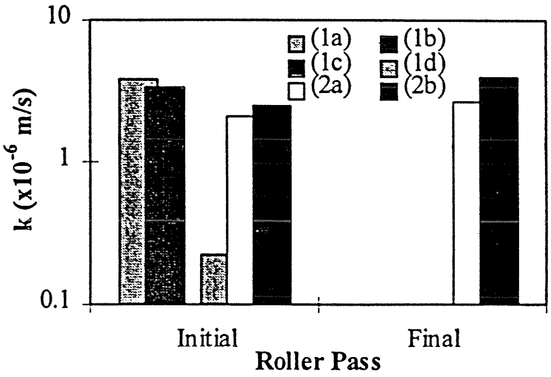

Figure 3 Hydraulic conductivity (k) at the edge of the roller mass on embankment A at; (a) 0.25 m depth on channel side, (b) 0.25 m depth on paddock side, (c) 0.5 depth on channel side, (d) 0.5 m depth on paddock side, after 0 and 15 roller passes.

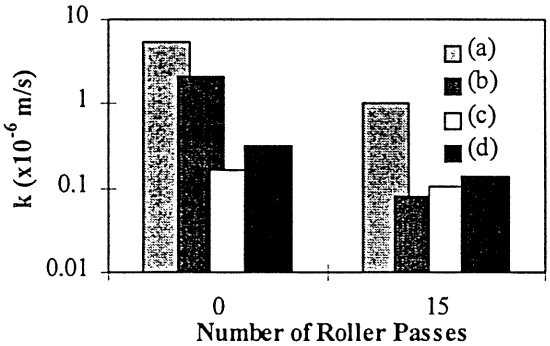

Figure 4. Hydraulic conductivity (k) at the edges of embankments A (1) and B (2) at; (a) 0.25 m depth on channel side, (b) 0.25 m depth on paddock side, (c) 0.5 m depth on channel side, (d) 0.5 m depth on paddock side, after the final roller pass.

4.5 Penetration Resistance

The cone penetrometer is a quick and easy method to determine the effectiveness of an impact roller. Shear strength can be related to soil density using penetration resistance data for a particular moisture content and soil. Penetration resistance before the application of an impact roller can be compared to readings after compaction, and so giving a qualitative measure of the effectiveness of the roller in changing the soil density. However, the shear strength and so the cone penetrometer readings are significantly affected by soil moisture content. Thus, determining relationships between shear strength and soil density for differing soil types and moisture contents can be difficult in general.

Results obtained for the penetration resistance of the two embankments differed considerably. Penetration resistance from embankment A is shown in Figure 5. This shows that after 15 roller passes the penetration resistance increased, suggesting the compaction had been successful. The penetration resistance from embankment B shown in Figure 6, however, indicated the impact roller had little effect on the soil density at this site. Although the penetration resistance is affected by different moisture contents, the moisture content in embankment B would not have changed during the compaction process, so should not affect penetration resistance comparisons.

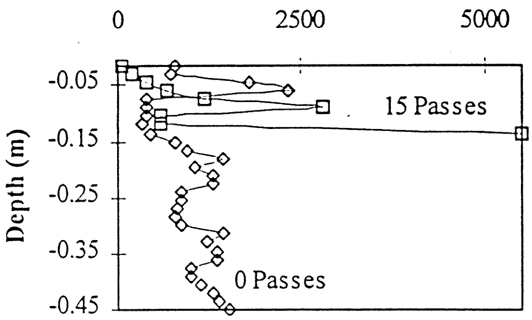

Figure 5. Penetration resistance at the centre of embankment A after 0 and 15 roller passes.

The impact roller was not designed to compact thin layers (Golder Associates Pty Ltd, n.d., Section 6) due to the top 100mm being loosened by the impact and shearing action of the roller (Chester, 1994). Regardless of the number of passes, compaction of the top layer will not increase. This characteristic of the impact roller serves to break up existing dense layers within the soil close to the surface. This is confirmed by the penetration resistance obtained in field tests on both embankments which rarely reached 3000 kPa within the top 0.1m as detailed in Figure 5. Below this depth in embankment A, penetration resistance often increased rapidly to over 5500 kPa. The destruction of dense layers by the impact roller was not limited to the top 0.1 m however, as an increased penetration resistance coinciding with vehicle wheel tracks on both embankments was destroyed by the roller after five passes as shown in Figure 7.

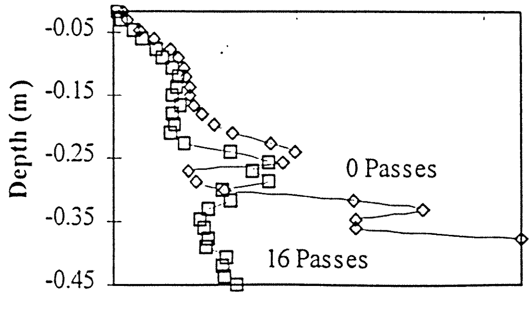

Figure 6. Penetration resistance at the edge of embankment B after 0 and 16 roller passes.

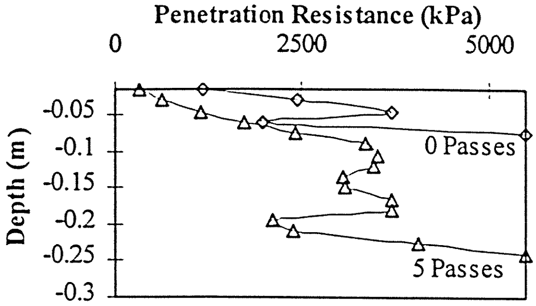

Figure 7. Penetration resistance under an existing wheel track on embankment A after 0 and 5 roller passes.

4.6 Settlement

The impact roller is increasingly being used as a proof roller for identifying weak spots in the soil (Clifford and Bowes, 1995) since an increased impact roller penetration or an increase in localised settlement of the surface may indicate weak spots. Costain Australia Limited (1988) found that proof rolling with an impact roller was successful at reducing settlement after compaction. Despite the benefits with measuring settlement, tests during field trials were not extensive enough to determine weak spots in the embankments.

A limitation of the impact roller was demonstrated during field trials, as remedial work was required. The impact roller is ineffective when settlement under the roller mass is in excess of 0.2 m. This is due to the roller mass landing on the roller frame rather than the ground. This problem has implications for all impact roller applications since there is a potential need for earthworks during rolling, thus increasing costs associated with this technology.

Comparisons between Figures 8 and 9 show the difference in settlement on embankments A and B respectively. Whitlow (1990) suggests that settlement and compaction are related such that small settlement may indicate poor compaction, while large settlement may indicate higher degrees of compaction. Thus, the small settlement on embankment B further suggests ineffective compaction, consistent with the previous observations on penetration resistance which showed negligible increase in shear strength in embankment B. Given that the moisture content at 0.5 to 0.75 m was about 3% above optimum (standard compaction) in embankment B, it appears that this moisture content may be too high for effective compaction of this soil.

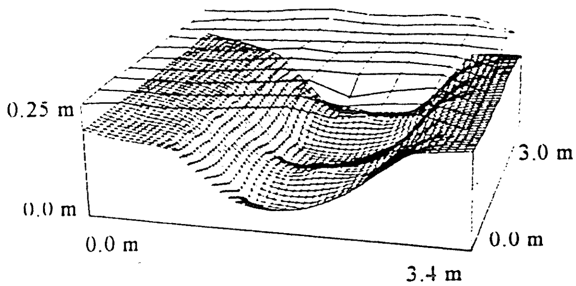

Figure 8. Settlement of embankment A after 0 and 15 roller passes.

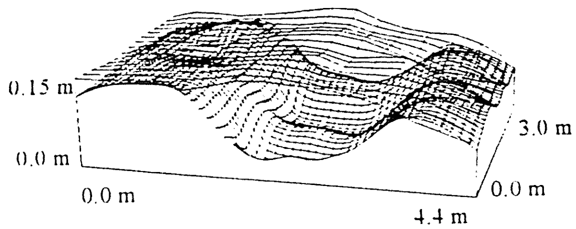

Figure 9. Settlement of embankment B after 0 and 16 roller passes.

5. GUIDELINES

Due to the minimal existing guidelines for impact roller operations, the following recommendations for routine use of the roller have been made. Similarly, recommendations for more extensive testing of the impact roller in new applications and during research are given. All recommendations made are aimed at providing a basis for future quality assurance standards in the industry, but can only be regarded as preliminary until a more extensive research program is undertaken.

5.1 Routine Impact Roller Testing

Routine testing should occur during all impact roller applications except when the extensive testing procedure is used. A suitable initial soil moisture content of the compaction site is critical for the success of the impact roller. Accurate and reliable data should be obtained by either the operator or an appropriate geotechnical testing authority as determined by AS 3798 Appendix B (1990) using the recommendations outlined. Routine testing procedures should however, be aimed at minimising time and expense whilst still providing an adequate indication of the impact roller success.

The routine testing procedure undertaken according to appropriate Australian Standards and at a representative depth (eg. half the expected depth of compaction) prior to compaction should include determining:

- field moisture content;
- optimum moisture content;
- penetration resistance or in-situ density tests.

After the compaction process, testing may be limited to penetration resistance or in-situ density tests thus giving a quick indication of the effectiveness of the impact roller.

5.2 Extensive Testing Procedures

For investigating new applications of the impact roller technology and for research, a detailed, extensive testing procedure is crucial. Accurate and reliable data should be obtained by an appropriate geotechnical testing authority as determined by AS 3798 Appendix B (1990) using the recommendations outlined.

The extensive testing procedure prior to compaction should include the routine procedures (section 5.1) at least and the following additional work guided by the appropriate Australian Standards:

- soil classification of the site and the production of a soil type map;
- field moisture content determination through the complete soil profile to be compacted;
- initial hydraulic conductivity through the complete soil profile to be compacted using appropriate equipment, such as Guelph Permeameter;
- penetration resistance of the site or in-situ density testing; and
- an initial site survey before the application of an impact roller.

To complement these procedures, an appropriate statistical sampling system should be used to guide initial testing such as ISO 9091 (1994). This statistical sampling system should be employed in conjunction with testing in known problem areas. Results of pre-compaction testing should be compiled into an appropriate report.

At regular intervals during the compaction process (ie. at every third of the total roller passes) the same field tests as for pre-compaction testing should be applied. The field moisture content, however, should be determined only if delays during compaction have been encountered, especially if due to rain.

After the final impact roller pass, further testing should be undertaken to determine the effectiveness of the compaction process and ensure problems such as shattering are not evident. Field testing procedures outlined, with the exception of moisture content determination, should be repeated. Problems relating to high hydraulic conductivity or low density, after checking the moisture content, should be remedied with further impact roller passes.

5.3 Areas Requiring Further Investigation

One of the major limitations of the current study is that only one soil type has been investigated. Although the soil investigated is typical of many found in agricultural areas, it is hard to generalise the findings until a wider range of soils have been investigated.

Current guidelines and recommendations made in this paper for the operation of impact rollers also fail to adequately address several issues. These include minimising adverse effects resulting from soil shattering, and providing a uniform basis for the choice of testing equipment so that testing time is minimised whilst ensuring adequate and uniform data is obtained. Thus, further investigations are required to increase the potential for impact roller success, while continuing to develop quality assurance in the impact roller industry.

6. CONCLUSIONS

The impact roller offers potential in minimising water losses in agriculture from seepage through compaction. Investigations at a field site showed increased density and reduced permeability in a highly plastic clay soil in a cotton growing area after application of an impact roller. Improvements were not uniform however, and inadequate compaction due to high moisture content in one location and evidence of soil shattering (leading to increased permeability) were observed.

Current guidelines are inadequate and this study suggests some preliminary improvements. Impact rollers do have a role to play in agricultural industries but further research is needed to ensure that they are used in the most effective manner.

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