PROOF ROLLING REVISITED

Tony Colenbrander [1] and Robert L Smith [2]
[1] Group Manager, GHD Geotechnics, Sydney
[2] Senior Pavements Engineer, GHD Geotechnics, Sydney

ABSTRACT

Proof rolling has been used as a technique to prove satisfactory foundation strength for earthworks structures for many years. It is a crude test, but effective in identifying obvious weak spots in subgrade soils that are predominantly of adequate strength to support embankments or pavements. However, problems can arise when proof rolling is inappropriately specified or the limitations of the test are not fully understood.

This paper provides an overview of the test method and its limitations. It also reviews some experiences where poor understanding of the test method has resulted in subsequent pavement failure or the construction of pavements that exceed design requirements.

A theoretical analysis of proof rolling deflections is provided for a range of subgrade soil strengths, under a specified proof roll loading nominated in AS3798. This analysis demonstrates the need to specify proof roll loading that is consistent with specific pavement design requirements rather than adopting a “one size fits all” approach.

Issues that need to be considered when specifying and performing proof roll tests are addressed.

1 INTRODUCTION

Proof rolling, or test rolling as it is sometimes called, is a crude and quick technique that has been used for many years to prove satisfactory foundation strength for earthworks structures. It involves the application of a nominated roller drum or wheel load to the foundation soil surface and observation of the impact of the load on the subgrade soil. Typically, the foundation is deemed satisfactory if no visible deformation or springing is observed.

The test was originally devised to assess the strength or bearing capacity of pavements and their foundations. It is an effective tool to identify obvious weak spots in large soil surfaces where compaction may be poor or subgrade moisture conditions too high to support compacted fill. The proof rolling technique was subsequently applied to many other earthworks conditions, to the extent that it is now the norm to find proof rolling requirements in most earthworks specifications. Unfortunately, the limitations of the test are not always well understood by those preparing the specifications or those supervising the testing, which can lead to inappropriate applications of the technique and consequent problems.

Proof rolling is a crude tool and does not provide a “one size fits all” solution to earthworks foundation preparation because many variables other than the density of the foundation soil will impact on the outcome. The material type, soil moisture condition, soil stiffness, applied load and interpretation of “visible deformation” as an acceptance criterion are parameters that need to be carefully considered. Typically, an experienced geotechnical engineer should be engaged to specify and supervise proof rolling because they should have sufficient understanding of soil mechanics to interpret the results and provide appropriate advice on required foundation treatments. The likelihood of adopting expensive or inappropriate foundation treatments is significantly increased where this does not occur.

This paper provides an overview of proof rolling and its limitations. It also reviews some experiences where poor understanding of the test method has proved inappropriate, resulting in subsequent subgrade failure, redesign of foundation support or the construction of road pavement foundations that exceed design requirements.

2 WHAT ARE WE MEASURING?

The objective of proof rolling is usually one or several of the following:

- To identify zones of poor compaction (as evidenced by large plastic deformation)
- To identify zones of high moisture content in clayey foundation soil (where “springing” or large elastic deformation occurs)
- To prove that the subgrade soil has adequate stiffness (as evidenced by very small elastic deformation) to comply with pavement design requirements – typically defined in terms of a design subgrade CBR strength for road pavements.

The act of proof rolling has the following impacts on these objectives:

- It is likely to improve the density of poorly compacted soil (assuming suitable soil moisture conditions) and may thus resolve this weakness in the foundation soil (a positive impact).

- Where the near-surface soils are cohesive and well dry of optimum moisture content (OMC), the transient in situ soil strength is likely to be high, even when the soil density is low. In these conditions the proof rolling criterion of “no visible deflection” may be met even though compaction/soil density is unsatisfactory (a negative impact).
- In areas of high soil moisture content, the “springing” action under proof rolling acts as a soil pump. Continued rolling is likely to draw more moisture into the soil, thus further weakening it (a negative impact).
- Where proof rolling is intended to assess soil stiffness and visible deformation is observed, further rolling of weak cohesive soils is likely to result in progressive bearing capacity failure of the soil and even greater deformation (a negative impact).

These potentially contradictory impacts demonstrate the need for careful specification of proof rolling and a clear understanding of the objectives by the person conducting the testing. They also show that the intuitive reaction that further rolling will improve the situation can be counterproductive when applied to proof rolling of cohesive soils.

3 FACTORS INFLUENCING PROOF ROLLING

Soil movement under proof rolling is complicated by the following factors:

Material type: Non-cohesive soils (clean sands and gravels) behave differently to cohesive (clayey) soils under compaction. Clean sands are usually easily compacted but localised bearing capacity failure typically occurs at the surface under wheel loads, so proof rolling is generally inappropriate unless it can be carried out after placing a thin capping layer to confine the sand. Well graded granular soils with relatively small fines content are readily compacted and typically insensitive to moisture variation and over compaction. Such soils typically compact to form a stiff material that is insensitive to the negative impacts of proof rolling. However, cohesive soils with a clay content greater than about 12% are sensitive to the negative impacts outlined above and the discussions in this paper are generally confined to the behaviour of such soils.

Soil moisture: The strength/stiffness of clayey soils is highly dependent on the soil moisture content. “Dry” clayey soils, even poorly compacted soils, are strong and generally do not deflect under proof loading, while moist clayey soils typically have low stiffness and CBR values. Poorly compacted clayey soils are a particular problem as they can be very stiff when dry but collapse to “mud” when wetted up. Unfortunately there is often no soil moisture requirement associated with proof rolling and this is a major weakness of the test method. The authors are aware of a number of cases where the cause of road and railway track subgrade failure soon after construction could be attributed to proof rolling being conducted on weak foundation material when it was in a dry condition. Turnbull and Foster (1960) report a case history where heavy proof rolling of an aircraft pavement failed to prevent premature serious rutting under subsequent aircraft traffic because the proof rolling was undertaken after the base course had dried out.

Soil stiffness: This is a function of many factors including material type, origin, density, cementation and moisture condition. The impact of soil stiffness on deflection under Benkelman Beam truck loading conditions is illustrated in Figure 1 (RTA 1991), where stiffness is defined as Subgrade Modulus (E). The figure shows the range of subgrade deflections that may be anticipated for various CBR values, on the assumption that E (in MPa) is in the range of 5 x CBR to 20 x CBR, as suggested by a database of test results (Shell 1978). Assuming that the limit of visible deflection is about 1.5 mm, Figure 1 shows that it is possible for proof rolling with a Benkelman Beam truck loading to result in the rejection/failure of deep subgrade soils with CBR strength of less than about 10.

It is worth noting that Austroads (2004) adopts a relationship of E=10 x CBR for pavement design purposes, based on a median value derived from the above database. Knowledge of the wide spread of results on which this relationship is based should encourage caution in its application. Using this criterion, the lower limit subgrade CBR strength likely to pass the Benkelman Beam truck proof roll test is about 5 (i.e. only subgrades with a CBR > 5 will pass).

Applied load: Assuming adequate compaction and near-equilibrium soil moisture conditions, proof roll deformations will be a function of the stiffness of the soil being tested and the applied stress. Care should therefore be exercised when nominating the proof roll loading for particular subgrade stiffness requirements. For example, if the design subgrade CBR for a road pavement is (say) 4%, then the proof roll loading for foundation acceptance should be such that it does not induce visible deformation on a subgrade soil with a modulus of 40 MPa. This level of sophistication is generally ignored in proof rolling specifications and a “one size fits all” approach is adopted. The authors are aware that Vicroads experience has shown that the quantity of subgrade replacement for new road projects generally exceeds tender estimates. This is hardly surprising in view of the heavy proof roll loading nominated in their standard specification in relation to generally low design subgrade CBR values.

Roller type: Smooth drum rollers are not considered ideal for proof rolling because the drum can bridge over localised weak spots and the roller imprint often leaves ridges along the edges that make the interpretation of visible deformation more difficult. Pneumatic tyre rollers are preferred because they apply a uniform pressure to the soil and the response of the soil is localised rather than spread over a drum width. Note that pneumatic tyre rollers and trucks are likely to produce different proof rolling responses, even if operated at the same tyre pressure, because they have different tyre wall configurations.

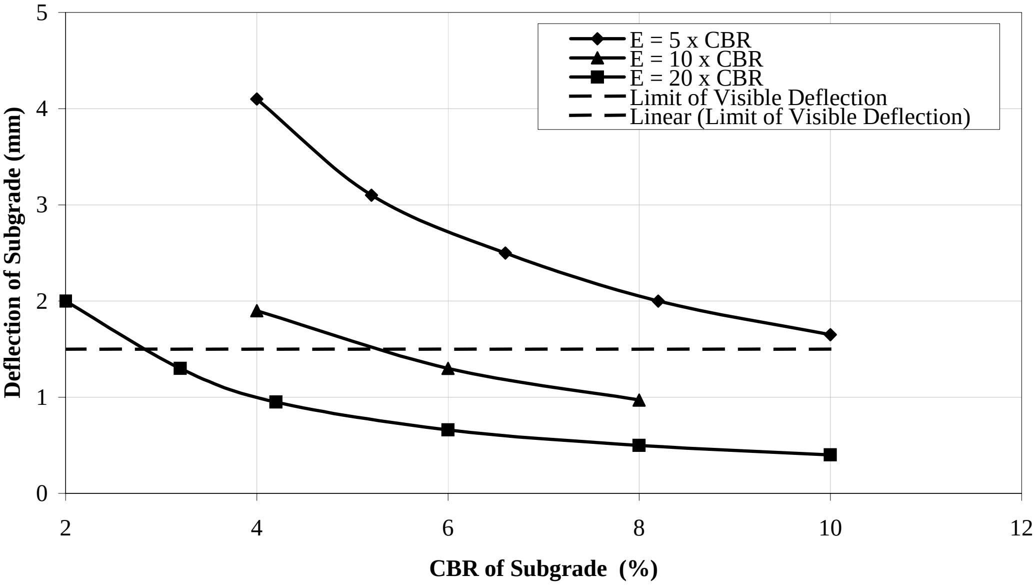

Figure 1: Calculated Elastic Deflection vs Subgrade CBR Under Benkelman Beam Truck Loading.

Interpretation of visible deformation: There is much debate and little published information on what constitutes “the limits of observable deflection” under proof rolling. Brown (1966) describes a methodology for pavement deflection observation and divided observations into three categories. He also suggested limits for each category, based on a series of visual observations of a loaded truck (with a “standard axle” of 8 tonnes on 4 tyres) and subsequent measurements with a Benkelman Beam. The average measured deflection for the category described as “barely visible” was 0.6 mm while “marked deflection” was 1.5 mm. Williams (1982) defined movement of 1.2-1.5 mm as the limit of visible deformation under a proof roller. This is consistent with the findings of Brown. RTA (1991) notes that tolerable maximum deflections of 1 to 2 mm are sometimes specified at subgrade level, suggesting that this is the limit of visible deflection. Others may contend that it is hard to see deflections of less than 3 mm. Factors that could influence the definition of “visible deformation” and thus the outcome of proof rolling include: the magnitude of the applied load (which defines the size of deflection bowl), strength of eyesight of the observer, the position of the observer (standing or squatting) and, importantly, the speed of the roller because slower speed amplifies the visual effect. Clearly there is significant scope for disagreement and operator sensitivity in this regard.

Based on the above evidence, it is reasonable to adopt a value of 1.5 mm as the limit of visible deformation under a carefully observed proof rolling test.

Number of passes: As discussed in Section 2 above, the number of passes specified for proof rolling could affect the result. When proof rolling is carried out *after* compaction (as specified in AS 3798-2007) then two passes should be adequate. Specifications should clearly distinguish between the work required to achieve compaction and the number of passes required for proof rolling. Typical loose wording such as “*There shall be no visible deflection following six passes of a roller of not less than 12 tonne mass*” should be avoided. In this case it may be assumed that the first four passes are intended to compact the surface, with proof rolling being assessed on the last two passes. If the surface has already been adequately compacted prior to “proof rolling”, then the additional compactive effort could overstress the surface and result in failure of a relatively weak subgrade that was of adequate strength to support the required load (such as a road foundation with a relatively low subgrade CBR).

4 CURRENT PROOF ROLLING SPECIFICATIONS

Table 1 summarises key requirements from a number of commonly used proof rolling specifications. The details provided in the columns shaded grey do not form part of the specifications but are interpreted from them.

An assessment of the specifications outlined in Table 1 reveals the following:

- AS 3798-2007 has adopted the VicRoads proof rolling specification as a national standard. This shows that it is well regarded in the construction industry. This test is referred to below as the AS

3798 proof rolling specification. While the test method is the same, it should be noted that test rolling in AS3798 is targeted to proving effective compaction of earthworks while Vicroads applies the test *(inter alia)* to proving subgrade soils.

Table 1: Commonly Used Proof Rolling Specifications.

Authority/ Specification	**Pneumatic Tyre Roller**			**Static Smooth Drum Roller**			**Comments**
	Plant Mass (min)	Tyre Pressure (min)	Conforming Truck Mass/Axle Configure	Plant Mass (min)	Load/m Width (min)	Plant Mass for 2.1m Wide Roller [#]	
VicRoads Spec Section 173.03	20 t	450 kPa	22.5 t* 1 x SAST 1 x TADT	12 t	6 t/m	>18 t	Adopted by AS 3798-2007
RTA Test Method T198 (Proof Rolling)	4.5 t/tyre	600 kPa	Multi-Tyre Roller	12 t	-	>12 t	Newer multi-tyre rollers are too light to comply.
RTA Test Method T160 & T199 (Benkelman Beam)	8.2 t	550 kPa	SADT	-	-	-	Tight spec on tyres and spacing.
Australian Standard 3798-2007 Clause 5.5	20 t	450 kPa	22.5 t* 1 x SAST 1 x TADT	12 t	6 t/m	> 18 t	As per VicRoads Spec 173.03
	8 t	550 kPa	Highway Truck Rear Axle(s)	-	-	-	Incorporates Benkelman Beam truck loading

*Max legal load

[#] Modern self-propelled smooth drum roller with single drum and 2 rear tyres.

SAST = Single axle single tyre

TADT = Tandem axle dual tyres

- The AS 3798 pneumatic tyre proof rolling specification is designed so that a conventional legally loaded tipper truck or water tanker with the axle configuration in Table 1 can be used for proof rolling.
- The AS 3798 specification nominates a minimum tyre pressure of 450kPa, which is low for modern construction plant. The specification does not consider the impact of tyre pressure variation, which can be significant (see Figure 2).
- Most modern self-propelled vibratory smooth drum rollers greater than 12 tonne mass that are commonly used in earthworks construction have a drum width of 2.1 m or more. This implies that heavy plant with a total mass greater than 18 tonnes will be required to comply with the AS 3798 specification.
- RTA Test Method T198 was written for older model multi-tyre rollers and the newer models are too light to comply with the specification. Note that the construction of truck and roller tyres can differ, which will affect their load response.

5 SUBGRADE CBR AND DEFORMATION FOR AS 3798 PROOF ROLL TEST

The impact of the AS 3798 pneumatic tyre proof roll specification on weak subgrade soils has been analysed and the findings are presented below. A similar analysis on the smooth drum roller specification was considered but abandoned due to its complexity. Determination of contact pressures beneath rigid smooth drum rollers depends on a range of factors including the drum diameter and the amount the drum penetrates into the soil surface (which will depend on the soil modulus). Both these parameters must be known to determine the static linear load applied to the soil by the drum. Further, cross-anisotropic elastic analyses of strip loading with a length to width ratio of about 20 to 1 are not straight forward.

CIRCLY software was used to calculate elastic deformation for a range of subgrade CBR values under a typical 14.5 tonne dual tyre tandem axle. This represents the rear tyre loading for a 20 tonne truck with the conforming configuration given in Table 1. Deformation under the SAST front axle was not assessed.

Analyses were conducted for both the specified minimum tyre pressure loading of 450 kPa and the more typical 750 kPa tyre pressures currently used by trucks. A subgrade soil thickness of 1.5 m was generally adopted with a limited assessment of a 1.0 m soil thickness to assess the sensitivity of this parameter. Typical Austroads (2004) design parameters were adopted for subgrade modulus (E = Ev = 10 x CBR), Ev/Eh = 2 and Poissons Ratio = 0.45 (where Ev and Eh are the vertical and horizontal modulus respectively).

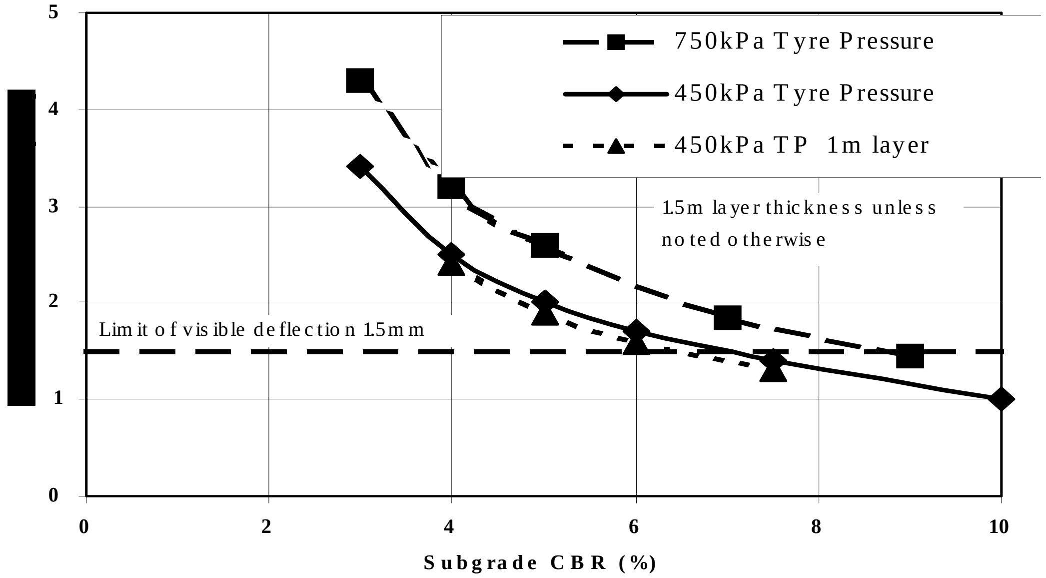

Figure 2: Calculated Elastic Deformation Under 14.5t Tandem Axle (20 Tonne Truck).

The results of the analysis are plotted on Figure 2 and show the following:

- Tyre pressure has a significant impact on soil deformation under proof loading. The deformation difference between 450 kPa and 750 kPa tyre pressure is about 0.5mm for CBR = 6 increasing to 1 mm at CBR = 3.
- Elastic deformations of 3.5-4.5 mm can be expected for subgrade soils with CBR = 3 under the nominated proof load. This implies that such soils would fail the proof load test and would have to be removed and replaced.
- With the limit of visible deformation taken as 1.5 mm, the nominated proof load will fail subgrade soils with CBR less than about 7 to 8 (depending on tyre pressure).
- The elastic deformation under proof loading is more sensitive to tyre pressure than to the subgrade soil thickness.

It should be noted that the applied stress on the subgrade soil during proof rolling will be close to the tyre pressure (e.g. 450 kPa to 750 kPa) but the stress in service will be much less. The test load / tyre pressure is thus significantly greater than the required serviceability condition.

These findings are consistent with the following guide for construction plant trafficability on weak subgrades, as reported by CRB (1960), modified to reflect construction plant available at that time:

Table 2: Trafficability of Weak Subgrades.

CBR (%)	***Construction Plant Traffic Capacity***
> 6	Trafficable by normal tractors, rubber tyred plant and padfoot rollers
> 4	Subgrade passable to rubber tyred and tracked vehicles but will be damaged
< 2½	Impassable to single rear axle trucks and 11 tonne graders
< 1	Impassable to all vehicles including tracked tractors

It is considered that the above guide has stood the test of time and remains valid for *in situ* CBR values.

The authors are aware of a section of freeway recently constructed in Victoria where the quantity of "unsuitable" subgrade material removed and replaced was more than 250% of the quantity that could reasonably have been foreseen on the basis of the geotechnical testing undertaken for the project. The design subgrade CBR value for the pavement design was 4 and the VicRoads proof roll test was applied to prove subgrade strength prior to the placing of fill. Having assessed (and dismissed) various other factors likely to have impacted on the quantity of unsuitable subgrade, it was concluded on the basis of the findings shown in Figure 2 that a significant quantity of subgrade soil that complied with the subgrade CBR design requirement had been unnecessarily removed as "unsuitable" because the proof roll test was failing subgrade material with a CBR strength of up to about 8.

6 CONCLUSIONS

While proof roll testing has been routinely used for more than half a century, little has been written about the test for many years and the processes at work do not appear to be well understood by the current generation of geotechnical engineers. The purpose of this paper was to revisit the subject to provide a better understanding of the limitations of the test and to offer improvements in the way it should be specified.

Our findings suggest that the AS 3798 / VicRoads proof roll test is too heavy for weak subgrade soils and that more attention needs to be paid to tyre pressures of the test vehicle. The load per wheel rather than an overall mass should be specified. The other important factor to be specified is the number of passes as this will affect the potential to build up pore pressures during proof rolling, which would not occur in service.

The size and capacity of earthmoving equipment has increased over time, bringing with it improved efficiencies and lower costs for earthworks construction. However, proof roll testing appears to be a casualty of this "bigger is better" syndrome and we now have a national proof rolling standard that may be inappropriate for use on weak subgrade soils. Care must therefore be exercised when specifying proof roll test loading to ensure that the nominated load is aligned with the subgrade design strength, typically specified in terms of CBR value.

There is scope for further research and review of the proof roll test methods listed in Table 1 to improve uniformity and to provide a range of proof rolling specifications for various subgrade stiffness conditions rather than a "one size fits all" approach. Attention also needs to be paid to the definition of "visible deformation" and how this can be controlled or standardised.

A major flaw of many proof roll testing specifications is the disregarding of soil moisture when conducting the test. The authors are of the opinion that when soil moisture conditions are not known prior to proof rolling, in situ moisture content and Atterberg limit testing should be conducted in conjunction with proof roll testing so that the supervising engineer is able to assess the relative moisture content and plasticity of the soil and thus make a rational decision as to the efficacy of the test.

7 REFERENCES

Austroads (2004) *Pavement Design - A Guide to the Structural Design of Road Pavements* Austroads Publication AP-G17/04

AS3798-2007 *Guidelines on earthworks for commercial and residential developments* Standards Australia

Brown E C (1966) *Test Rolling as a Tool in Pavement Evaluation* Proc ARRB Conf Vol 3 Part 2 p775 to 786 including Discussion

CRB (1960) *Construction of Pavements on Soft Subgrades* Engineering Note No. 65, June, Country Roads Board of Victoria

RTA (1991) *Concrete Pavement Manual – Design and Construction* Document No. TP-GDL-015, Edition 2, Revision 0, Dec, Roads and Traffic Authority, NSW

RTA (various dates) Materials Test Methods

- T160 Benkelman Beam Deflection Test (Feb 2001)
- T198 Proof Rolling Test (Feb 2005)
- T199 Deflection Monitoring Test (Feb 2005)

Shell (1978) *Shell Pavement Design Manual – Asphalt Pavements and Overlays for Road Traffic* Shell International Petroleum Company Limited, London

Turnbull W J & Foster C R (1960) *Proof Rolling of Subgrades* Highway Research Board Bulletin No. 254, Washington USA

VicRoads (2003) *Section 173 - Examination and Testing of Materials and Work (Roadworks)* Standard Specifications for Roadworks and Bridgeworks.

Williams M L (1982) *Field Measurement of Density - Methods of Assessment Based on Judgement* Proceedings of NAASRA/ARRB Workshop on the Use of Relative Compaction in the Control of Roadworks, Dec, Aust Road Research Board