PROCEEDINGS

2018 AUSTRALIAN GEOMECHANICS SOCIETY VICTORIAN SYMPOSIUM

Geotechnics and transport infrastructure

Wednesday, 24 October 2018, 8:00am – 6:00pm
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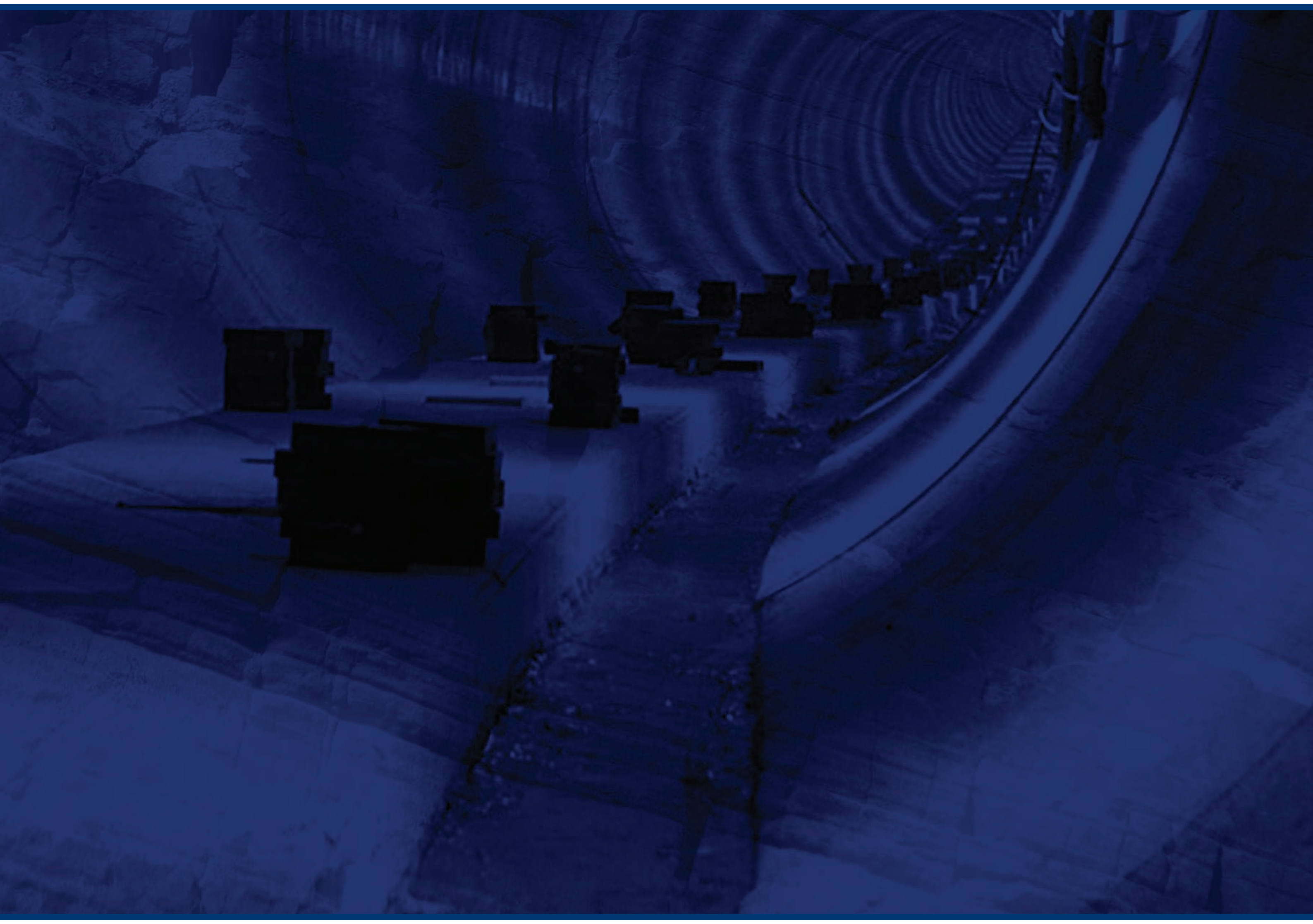

AUSTRALIAN GEOMECHANICS SOCIETY
VICTORIA CHAPTER

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PREFACE

The Victorian chapter of the Australian Geomechanics Society invited academics and practitioners in the field of geotechnical and ground engineering to attend the 2018 Australian Geomechanics Society Victorian Symposium on 'Geotechnics and transport infrastructure' held on 24 October 2018.

In recent years Victoria has seen significant investment in transport infrastructure as part of a plan to manage the demands of a growing population and expanding urban fringe. The construction of Melbourne Metro, a second crossing of the Yarra River, rail and freeway upgrades as well as numerous level crossing removal projects are just some of the major transport projects currently underway in Melbourne and regional Victoria. Many of these projects carry numerous complex geotechnical challenges.

The 2018 Australian Geomechanics Society Victorian Symposium covers a variety of geotechnical challenges associated with transport geotechnics and present overviews of current infrastructure challenges, state of the-art practices, innovation, new research results and case studies demonstrating applications of advanced techniques and cost effective solutions in the construction and design of local transport infrastructure. The Symposium brought together professional engineers, researchers, specialist contractors, regulators, educators and students to share and discuss their experiences on the topic of transport infrastructure and associated geotechnical challenges and applications.

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Keynote Address

The role of proof rolling in pavement construction

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ABSTRACT

Proof rolling of pavement subgrades is a key construction operation for all pavements but despite this there appears to be confusion about the process, the plant used and the evaluation criteria which is leading to subgrades that are adequate being condemned and having to be removed and replaced by stronger materials. The paper looks at the process and whether the plant currently being used as the proof roller is appropriate.

Keywords: pavements, compaction, proof-rolling

1 INTRODUCTION

The term proof rolling was introduced into the US Corps of Engineers guide specification for graded crushed aggregate base courses in 1957 (Turnbull & Foster, 1960). The process of using heavy rubber-tyred rollers to compact layers on airfields had been used since the mid-1940s.

Turnbull & Foster define proof rolling as a procedure to check the adequacy of normal compaction and to correct any deficiencies that may exist. They further describe the process as the application of a few coverages of a heavy rubber-tired roller.

In a paper prepared for the Indiana Department of Transport (Dunston et al, 2017) the authors note that the proof rolling results can only be properly interpreted if criteria are established that account for the interaction of equipment parameters (e.g. vehicle weight, tyre pressure, contact area), soil characteristics (e.g. soil type, moisture content), technique (e.g. speed, number of passes) and project specifics (e.g. new construction, rehabilitation).

It is interesting to note that a paper presented to an AGS Symposium in Sydney in 2007 (Colenbrander & Smith) concluded that while proof rolling was widely used it was poorly understood and that greater attention was needed to be given to the tyre pressure of the test vehicles and to the number of passes. It would appear that little has changed in the past decade.

Some of the confusion with the procedure and its evaluation appears to have arisen with the use of loaded trucks in place of pneumatic-tyred rollers as the proof roll plant. While the precise timing of this change is not known it is likely that truck tyre pressures at the time were comparable to those of a pneumatic-tyred roller but in the intervening years truck tyre pressures have increased significantly.

2 PROOF ROLLING METHODOLOGIES

2.1 Procedures

Proof rolling procedures are detailed in specifications issued by most State Road Authorities and in Australian Standard AS3798 "Guidelines on Earthworks for commercial and residential developments". A summary of the procedures are provided in Table 1. Main Roads Western Australia does not stipulate a procedure.

Table 1: Proof Rolling Procedures

Procedure	**Test Vehicle**					**Speed (kph)**	**No. of Passes**
	Pneumatic-tyred Plant			**Steel wheel roller**			
	Total Mass (t)	**Tyre Pressure (kPa)**	**Contact Area (m^2)**	**Total Mass (t)**	**Load Intensity (t/m)**		
Vic Roads Section 173	≥ 20	≥ 450	≥ 0.035	≥ 12	≥ 6	-	-
AS3798	≥ 20	≥ 450	≥ 0.035	-		-	-
	≥ 8/axle	≥ 550	-	≥ 12	≥ 6	-	-
IDM[a] 2018	VicRoads and AS3798						
RMS[b] NSW Test Method T198	≥ 4.5/wheel	≥ 450	-	≥ 12	-	3 – 10	-
	10,000l Water truck	≥ 600	-			-	-
QTMR[c] – MRTS04	RMS T198						
DPTI[d]-R10,	≥ 24t	≥ 450	≥ 0.035			3 - 10	3
	10,000l Water truck	≥ 450	≥ 0.035				
Dept. of State Growth – Tas.	VicRoads Section 173						

[a]Infrastructure Design Manual, [b]Road and Maritime Services, [c]Queensland Department of Transport and Main Roads, [d]Department of Planning Transport and Infrastructure

VicRoads

VicRoads stipulates a minimum load and tyre pressure but also a minimum contact area of 0.035 m^2. Considering modern truck tyres operate at a pressure of at least 700 kPa the minimum contact area would require a wheel load of at least 24.5kN or 2.5t[1]. For a legally loaded truck operating under General Mass Limits (GML) the axle loads are:

- Steer Axle 6t
- Single Dual-tyred Axle 9t
- Tandem Dual-tyred Axle 16.5t

Therefore, for a test vehicle at GML the wheel loads vary between approximately 2.05t for the wheels on the tandem axle and 3t for the wheels on the steer axle. Higher Mass Limits allow the load on the tandem axle to be increased 17t which would only increase the load per wheel to 2.13t. On that basis only the steer axle wheels would comply with the VicRoads minimum contact area. A typical 7-wheel pneumatic roller loaded to 3t/wheel (i.e. total mass exceeding 20t) and operating at a tyre pressure of up to 840 kPa would comply with the minimum contact area. But not all these combinations of tyre [pressure and contact areas would stress the subgrade equally.

The procedure does not stipulate a speed at which the proof roller is to be operated or the number of passes that must be applied to the area being proof-rolled. From that, it is concluded that for VicRoads the speed of operation is inconsequential and that a single pass is sufficient.

AS3798

The Australian Standard has adopted a procedure similar to that specified by VicRoads except that it separately stipulates load and tyre pressure requirements for a truck being used as a proof roller. Therefore, comments made in relation to the VicRoads procedure are applicable to this procedure.
The procedure using a highway truck permit the use of a tyre pressure other than 550 kPa so modern trucks would not be permissible as a proof roller under this Standard.

Infrastructure Design Manual

This Manual which is used by most regional and rural Councils in Victoria adopts a procedure based on VicRoads and AS3798 and hence comments above apply to this procedure.

Roads and Maritime Services (NSW)

The procedure includes a requirement that the roller be operated at fasts walking speed between 3 kph and 10 kph although the upper end of this range would seem to be well above what a normal person's walking speed. A speed between 3 kph and 5 kph would appear to be more achievable.

The stipulated minimum wheel load and tyre pressure for a pneumatic-tyred roller would result in a contact area approximately 3 times the minimum area stipulated in the VicRoads and AS3798 procedures. Even increasing the tyre pressure to 600 kPa would still provide a contact area more than double the minimum stipulated in the VicRoads/AS3798 procedure.

The requirement for the use of a 10,000 litre water truck is somewhat open-ended because the total mass and the wheel loads depend on the tare weight of the truck which presumably varies depending on the make and model of the truck. A tare weight of 10t the axle loads would likely be:

- Single steer axle: 5t
- Tandem dual tyred axle: 15t

While the contact area is not stipulated these loads would correspond to contact areas of 0.041 m^2 and 0.030 m^2 at a tyre pressure of 600 kPa. Therefore, using the VicRoads criterion the front wheels should be used as the basis for assessing the proof roll.

Queensland Department of Transport and Main Roads

The Department's specification references the RMS NSW proof roll procedure.

Department of Planning, Transport and Infrastructure, South Australia

The Department's procedure appears to be a combination of VicRoads and RMS procedures but is unique in that it requires multiple passes of the proof roller as part of its procedure. It also incorporates a speed requirement for the procedure.

The procedure using a 7-wheel pneumatic-tyred roller would require a wheel load of at least 3.5t. At the minimum stipulated tyre pressure that load would result in a contact area of 0.073 m^2

Department of State Growth, Tasmania

In 2016 the Department adopted the VicRoads Standard Specifications for Road works and Bridgeworks. Therefore, its proof rolling procedure mimics the VicRoads Section 173 procedure.

2.2 Evaluation Criteria

In addition to the variations in the proof rolling procedures there are also differences in the evaluation criteria as discussed below.

VicRoads

VicRoads Section 173 stipulates that under the proof roller there should be no visible deformation or springing. There are no actions stipulated for areas where visible deformation of springiness are detected.

AS3798

The assessment criteria are the same as those stipulated by VicRoads but includes the following rectification requirements:

> *"Any areas where visible deformation or springiness is detected have to be rectified and re-presented for proof rolling and where these areas are more than*

[1] The contact stress is taken to be uniform across the contact area and equal to the tyre pressure

20% of the area being proof rolled the entire area has to be ripped, recompacted and re-presented for proof rolling".

Infrastructure Design Manual

The Manual requires deflection under the proof roller to be no more than 2 mm within 300 mm from the wheel of the proof roller. It is not clear how the deflection is to be measured and it is also not made clear whether the distance from the wheel is taken along or transverse to the direction of travel. A shown in Figure 1 the curvature of the deflection bowl under a dual-wheel is less in the transverse direction so that 2 mm deflection at a point 300 mm offset transversely would be a weaker subgrade than 2 mm at a point 300 mm behind the wheel.

Where the areas which exhibit excessive deflection are more than 20% of the total area being proof rolled then the total area is required to be reworked. It is not clear what action is required where the locations are less than 20% of the total area.

Roads and Maritime Services (NSW)

The specification stipulates that the proof rolled surfaces must not exhibit visible deformation, rutting, or yielding and/or show signs of distress or instability.
There is no comment as to the rectification required of areas which do not comply with the requirements above.

Queensland Department of Transport and Main Roads

The evaluation criterion is perceptible surface deformation. In areas which exhibit perceptible surface deformation the soil is required to be removed and replaced and the rectification may be subject to additional testing, presumably further proof rolling.

Department of Planning, Transport and Infrastructure, South Australia

The procedure refers to observation of deformation under the proof roller but then states that areas that move under the loading of the plant are deemed to be unsuitable. There are no requirements for rectification of defective areas.

Department of State Growth, Tasmania

The evaluation criteria are the same as VicRoads.

2.3 Soil Characteristics

As noted by Colenbrander and Smith requirements for the soil conditions at the time of proof rolling are not well defined in any of the procedures. Some (VicRoads, AS3798, DPTI) require proof rolling to be undertaken immediately after compaction of the subgrade but others require proof rolling within 48 hours of completing compaction.

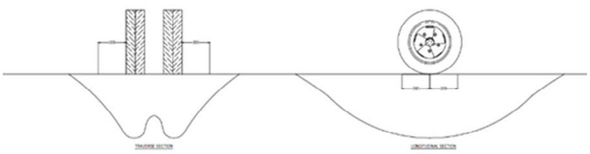

Figure 1. Deflection Bowls

That delay maybe sufficient to allow the subgrade moisture conditions to change from those at the time of compaction. For longer delays between compaction the procedures require the soil to be moisture conditioned and recompacted prior to proof rolling.

2.4 Summary

This review of the proof rolling procedures across Australia raises several questions:

- Are modern highway trucks with the higher tyre pressures still appropriate for proof rolling or should all proof rolling be conducted with pneumatic-tyred rollers
- Should proof rolling be evaluated on the basis of subgrade deflection (movement) or deformation (rutting);
- Should deflection be evaluated at the edge of the tyre or at some distance laterally from the tyre;
- Is the speed of the proof roller important
- Is a single pass of the proof roller sufficient or should multiple passes be used.

The following sections consider response to these questions as a means of reaching a more considered procedure for conducting and evaluating proof rolling.

3 EVALUATION TECHNIQUES

3.1 General

Apart from the procedure in the IDM, the procedures evaluate the condition of the subgrade on the basis "no visible" or "no perceptible" deformation, rutting, yielding or movement. Deformation would normally be considered to describe a permanent rut but in the author's experience is commonly interpreted as deflection or movement.

The difficulty with this evaluation standard is that "no visible" or "no perceptible" deflection is a highly subjective measure and in terms of how this standard impacts on the as-constructed pavement it would be useful to provide a more objective measure.

3.2 Deflection

In the 1960's the Commonwealth Department of Works introduced a procedure for evaluating the structural condition of airfield pavements (Brown 1968). The procedure involved towing a heavy pneumatic-tyred roller along the pavements at a speed of 2.5 to 4 mph (4 to 6 kph). Two observers walked alongside the roller and at regular intervals observed the rebound deflection of the pavement as the roller wheel passed by from a squatting position. The rebound deflection was recorded in accordance with the following qualitative scale:

- a- No visible deflection
- a Barely visible deflection
- a+ Clearly visible deflection
- b Marked deflection without any apparent deformation
- c Marked deflection as for "b" but accompanied by permanent deformation

Brown concluded that a standing observer would only be able to perceive movement that would be rated "b" by a squatting observer.

In order to calibrate this qualitative scale Brown conducted an evaluation of a road pavement and then measured deflections under a standard axle (18,000 lb, 85 psi) using a Benkelman Beam.

The visual ratings were compared with the measured deflections (Figure 2). The average deflection for locations rated as “b” was 0.06 inches (1.5 mm) with a range of 0.045 to 0.075 inches (1.1 mm to 1.9 mm). Therefore, on this evidence it is reasonable to conclude that the limit of visible deflection is no greater than 1.5 mm. Brown also measured deflections at offsets from the tyre of a heavy pneumatic-tyred roller with a wheel load of 25000 lb (11t) and a tyre pressure of 150 psi (1 MPa) (Figure 3).

This showed that the deflection at distance of 12 inches (300 mm) from the wheel was approximately 30% of the deflection at the tyre. Therefore, if the observer is assessing “visible” deflection at a distance of 300 mm from the tyre (i.e. 1.5 mm) the deflection at the tyre could be as much as 5 mm.

Considering these numerical limits of the visible deflection, it is possible to consider their impact on the “as-constructed” pavement. To do so it is necessary to translate the deflections under the axles of the proof roller to a deflection under at the standard axle loading which is defined as 8.2 t on a single dual-tyred axle at a tyre pressure of 566 kPa. For a single-tyred single axle and a dual-tyred tandem axle, the loads which induce the same deflection as the standard axle are 5.4 t and 13.5 t, respectively.

If the proof rolling is being conducted using a 10,000l water truck with a gross vehicle mass of 20t, axle loads of 5t on the steer axle and 15t on the rear tandem axle and a tyre pressure of 700 kPa. Subgrade deflections produced by these axle loads relative to the deflections produced by the standard loads are directly related to the 7th power of the ratio of the axle loads and to the ratio of the tyre pressure:

$$y_{\text{std load}} = y_{\text{actual axle load}} / \{(L_a / L_s)^7 x (p_t / p_{st})\} \quad (1)$$

where: $y_{\text{std load}}$: maximum deflection (mm) under the standard load for the axle group type
$y_{\text{actual axle load}}$: observed deflection (mm)
L_a : load on the axle (t)
L_s: standard load for the axle group type (t)
P_t : tyre pressure (kPa)
P_{st} : tyre pressure standard axle (kPa)

for the single axle:

$$y_{\text{std load}} = y_{\text{actual axle load}} / \{(5/5.4)^7 x (700/566)\} \quad (2)$$
$$= y_{\text{actual axle load}} \times 1.39$$

for the tandem axle:

$$y_{\text{std load}} = y_{\text{actual axle load}} / \{(15/13.5)^7 x (700/566)\} \quad (3)$$
$$= y_{\text{actual axle load}} \times 0.39$$

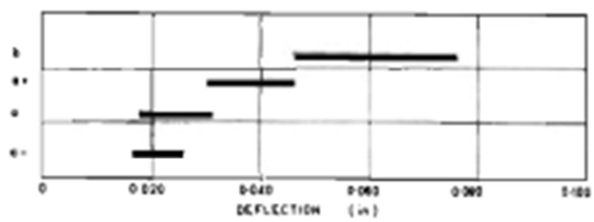

Figure 2 Visual Assessment scale and Benkelman Beam Deflections (after Brown, 1968).

Therefore, the limit of visible deflection when observing the steer axle would equate to 2.1 mm under a standard axle. For the tandem axle the limit of visible deflection equates to 0.6 mm deflection under the standard axle. If the observations are made at an offset of 300 mm from the wheel then the deflections under the standard axle are 7 mm and 2 mm for the single and tandem axle, respectively.

These deflections can be translated to deflections at the finished pavement surface using the method developed for designing the thickness of gravel resheeting of existing pavements (Austroads, 2011). The relationship between the maximum deflections before and after resheeting is based on the understanding that deflection reduces by 6% for each 25 mm thickness of granular material. The ratio of the surface deflection to subgrade deflection is given by the following equation:

$$y_{\text{surface}} = y_{\text{subgrade}} \times 0.94^{(t/25)} \quad (4)$$

where: y_{surface} : deflection (mm) at the final pavement surface under a standard axle
y_{subgrade} : deflection (mm) at subgrade level under a standard axle
t: pavement thickness (mm)

The surface deflection for varying thicknesses of pavement are presented in Table 2. These factors can be applied to the subgrade deflections to determine deflections at the pavement surface (Table 3). These deflections can then be used to determine the tolerable traffic loadings (Austroads, 2011) (Figure 4).

3.3 Deformation

Some procedures require that the subgrade be assessed on the basis of visible deformation i.e. rutting. Considering the transitory nature of the load the depth if rutting can be determined by the following relationship for immediate settlement of a footing:

$$S = qB\{(1-v^2)/E_u\} I \quad (5)$$

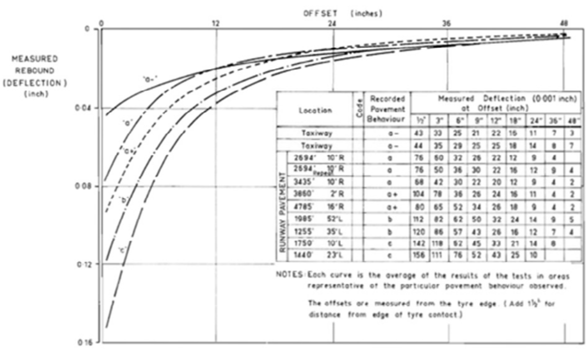

Figure 3. Benkelman Beam deflections at lateral offsets from the wheel

Table 2: Surface deflection factors

Pavement Thickness (mm)	Ratio of Surface Deflection to Subgrade Deflection
300	0.48
400	0.37
500	0.29
600	0.23

Table 3: Pavement Surface Deflections and Tolerable Loadings

Pavement Thickness (mm)	Surface Deflections (mm)				Pavement Loading (ESAs)	
	Single Steer Axle		Tandem Axle		Single Steer Axle	Tandem Axle
	Subgrade Deflections (mm)		Subgrade Deflections (mm)			
	2.10	7.0	0.6	2.0		
300	1.00	3.36	0.29	1.00	3 x 10^6 ; <1x10^3	> 1 x 10^8; 3 x10^6
400	0.78	2.59	0.22	0.85	> 1 x 10^8; <1x10^3	> 1 x 10^8 ; 2 x 10^7
500	0.61	2.03	0.17	0.67	> 1 x 10^8; 7 x10^3	> 1 x 10^8
600	0.48	1.61	0.14	0.53	> 1 x 10^8; 5 x10^4	> 1 x 10^8

where: S: settlement (mm)
q: applied stress (kPa)
B: footing width (m)
v: Poissons Ratio
E_u: undrained modulus (MPa)
I: shape factor = 1 for centre of circular loaded area

The interesting feature of Equation 2 is that S= 0 i.e. no visible indentation (rut) would imply a subgrade of infinite stiffness which is not possible.

Considering the steer axle of a 10,000l water truck, the applied stress is 700 kPa and the width of the loaded area is 0.211 m based on a circular loaded area. A Poisson's Ratio of 0.35 is adopted for the subgrade soil. On that basis equation 5 becomes:

$$S \approx 130/E_u \quad (6)$$

Crovetti (2002) provides the following relationship between CBR and undrained shear strength (C_u):

$$C_u \text{ (kPa)} = 15.5 \times CBR \quad (7)$$

For moderately over-consolidated medium plasticity cohesive soils (30≤PI<50) the undrained modulus and shear strength are related as shown in Equation (8) (NAVFAC DM 7.1, 1982)

$$E_u \text{ (MPa)} = 0.3\ C_u \text{ (kPa)} \quad (8)$$

Combining Equations (7) and (8) gives the following relationship between undrained modulus and CBR:

$$E_u = 4.65\ CBR \quad (9)$$

Using equations (6) and (9) the indentation depths of a wheel loaded at 2.5t and with a tyre pressure of 700 kPa can be determined for subgrades with CBR values ranging from 2% to 7% (refer Table 4). The rut depths tabulated above are for a static load. An earlier study

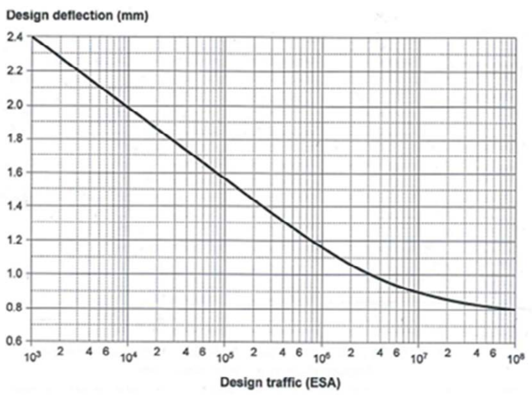

Figure 4. Tolerable Deflection

(Hambleton & Drescher, 2008) calculated rut depths for static and rolling wheel loads for a range of soil characteristics (Figure 5). The analysis is based on a rigid wheel which is valid for a stiff, highly inflated tyre which is truer of a pneumatic-tyred roller wheel. In addition, the analysis is based on a tyre diameter of 1.5 m. This approach has been used to assess the relationship between wheel load and rut depth for a 13/80 R20 tyre which is typical of a pneumatic-tyred roller applied to soils having CBR values ranging from 2% to 10% (Figure 6).

Based on the speed of loading the soil conditions have been considered to be undrained (Φ=0). Based on the analysis wheel loads between 1.5 t and 4.5 t and a rut depth of 25 mm can be used to confirm the subgrades with CBR values between 3% and 8%.
An acceptable depth of rut can be selected to reflect the CBR value of the subgrade at the time of construction and the acceptance criterion would be the uniformity of rut depth across the area being proof rolled.

4 DISCUSSION

In response to the questions posed earlier in this paper the foregoing analysis leads to the following conclusions.

Proof roller

A modern highway truck with its higher tyre pressures can be used to assess subgrades but the observer should be focussing on the front steer axle not the rear tandem axle. For some current proof rolling procedures a pneumatic-tyred roller or a non-highway vehicle would be required because the wheel loads stipulated in the procedure could be achieved by a legally loaded highway vehicle. The higher wheel loads and lower tyre pressures at which a pneumatic-tyred can operate will stress a greater depth below the subgrade but at a lower stress.

Evaluation Criteria

If deflection is to be used as the evaluation criterion then the observer should be assessing at a point offset laterally from the wheel on the steer axle by 200 mm. The criterion of no visible deflection if observed at the wheel produces an as constructed pavement which has a load capacity significantly greater than the required capacity of the design pavement. This is particularly so for local roads

Table 4: Depth of Indentation

CBR	E_u (MPa)	S (mm)
2	8.3	21
3	14	9
4	18.5	7
5	23.2	5.5
6	28	4.5
7	32.5	4

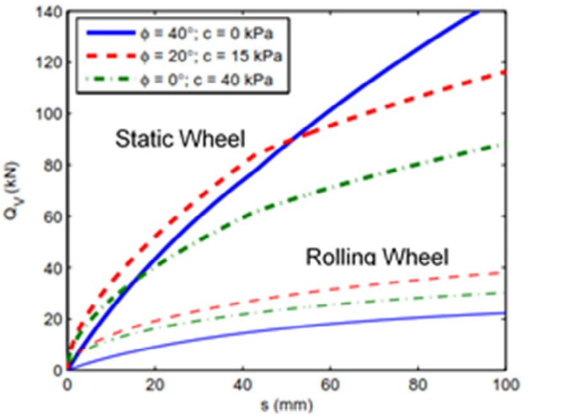

Figure 5. Rut depth vs Wheel load for static and rolling wheel

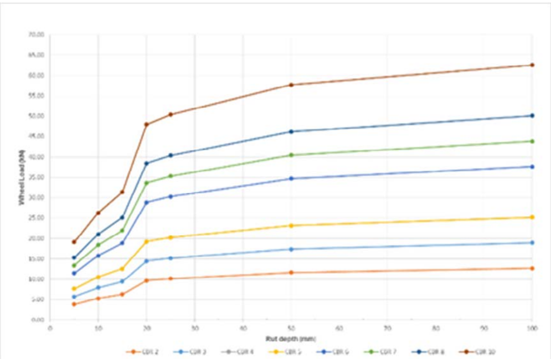

Figure 6. Wheel load vs Rut Depth

which typically have design traffic loadings between 1x10^4 ESA and 3 x 10^6 ESA. However the same criteria applied at a lateral offset of 300 mm as included in the procedure stipulated by the IDM can produce as-constructed pavements with load capacities less than required by the design.

In cases where visible deflection is detected the response is often to over-excavate the road formation and replace the 'defective" subgrade soil with better material or to stabilise the subgrade with lime and/or cement, both of which add to the cost of the construction. Additionally, for flexible pavements the use of cement within the upper part of subgrade has the potential to create a bound layer within an otherwise flexible pavement. Such a layer is likely to crack and impact on the medium to long-term performance of the pavement.

Deformation (i.e. rutting) provides a more objective and more easily measured basis of assessment although the criterion of "no visible deformation" is a physical impossibility. If deformation is adopted an acceptable rut depth can be set to be consistent with the CBR of the subgrade at the time of construction and the acceptance criterion can be based on the uniformity of the rut depth. The other part of the evaluation could look at the rate of increase of rut depth under successive passes of the roller then the proof rolling is simply densifying the subgrade and the result would be acceptable. If the rate remains constant or increases it is indicative of plastic deformation of the subgrade and would not be acceptable.

Regardless of whether deflection or deformation are adopted as the assessment, springiness should remain a criterion as it impacts on the ability to adequately compact overlying pavement layers.

<u>Speed of rolling</u>

Although not specifically part of this analysis it is noted that the limit of visible deflection derived from Brown's is based a wheel moving at 4-6 kph. The author has first-hand experience of the method described by Brown and can attest to Brown's view that at slower speeds the eye exaggerates the deflection while at faster speeds the observer has difficulty keeping pace with the roller.

<u>Multiple Passes</u>

Only one proof rolling procedure requires multiple passes of the roller. Multiple passes are not necessary where deflection is the basis of acceptance but can be important if deformation is the basis of acceptance.

<u>Soil Characteristics</u>

As has been noted by others (Turnbull & Foster, Colenbrander & Smith) it is necessary to ensure that at the time of proof rolling the subgrade is at the condition as when it was compacted. This is particularly so for the moisture conditions.

Shrinkage cracks which form in clay subgrades is also associated with delamination of the upper zone of the subgrade. The cracking and delamination results in loose plates of clay which then are unstable under the passage of the proof roller. Such movement is not indicative of the subgrade condition but is used to classify the subgrade as unsuitable and require the removal and replacement of a significant depth of the subgrade. Therefore, it essential that moisture conditions in the subgrade at the time of proof rolling should be the same as those at compaction. Where the moisture conditions have changed then the subgrade should be moisture conditioned and recompacted prior to proof rolling.

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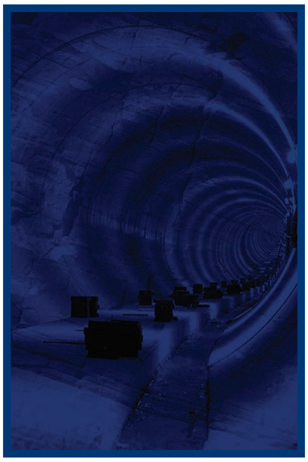
Geotechnics and transport infrastructure



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