GUIDELINES ON SETTLEMENT CRITERIA FOR DESIGN OF HIGHWAY PROJECTS

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ABSTRACT

This paper examines the implication of post-construction settlement and differential settlement on highway pavements constructed on soft soils by considering a number of a factors including: type of pavement, rate of settlement, ride quality, and likelihood of pavement distress. The main purpose of this paper is to provide some guidance and clarity on how differential settlement criteria should be specified and allowance made in the design, and in the selection of pavement types. Experience is drawn from monitoring and maintenance records gathered on various sections of the Pacific Highway Upgrade and other NSW roads. Extensive research has been carried out by the Roads and Maritime Services of NSW (RMS) and we have quoted extensively from their draft RMS (2009) “Guide for design and performance of concrete pavements in areas of settlement”. Structural performance of the pavement is considered in addition to ride quality functionality, and guidance is provided for designers to select the appropriate settlement and differential settlement criteria for highway projects. The RMS document uses radius of curvature as a basis for design, which is strictly speaking correct but difficult to predict when designing embankments on soft soils due to small allowable post-construction settlements. This paper provides some guidance on the correlation between the more commonly used limits on “change in grade” specified on recent road projects and “radius of curvature” and provides warning on the potential misuse of these values in assessing the length of transition zone required behind bridge abutments.

1 INTRODUCTION

One of the challenges for highway projects constructed over compressible soft soils or in areas susceptible to mine subsidence is assessing the impact of potential long-term settlement and differential settlement, and the impact on functionality of the pavement. Ground improvement for long lengths of pavement constructed over such areas is costly, and the adopted solution must meet capital cost and whole-of-life budgetary constraints. At the same time, the adopted solution must also meet road safety, ride comfort, and flood immunity requirements.

The allowable post-construction settlement and differential settlement are therefore intimately dependent on the choice of pavement and maintenance regime, and also the potential impact on existing and new structures.

2 DEFINITION OF TOTAL AND DIFFERENTIAL SETTLMENT

It is differential settlement rather than total settlement that causes pavement distress. There are two basic deformation shapes caused by differential settlement. These are concave and convex as illustrated in Figure 1.

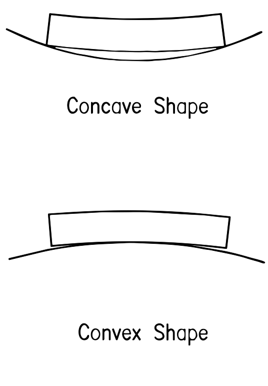

Figure 1: Pavement Deformation Shapes Caused by Differential Settlement (RMS, 2009)

These deformations can be expressed in terms of the radius of curvature, R, with smaller values of R being more critical to settlement induced stresses. Figure 2 shows the relationship between total and differential settlement of a concave settlement bowl.

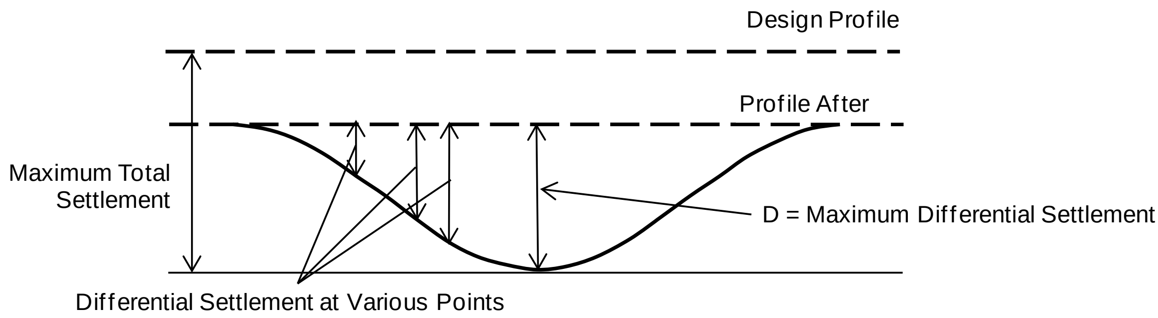

Figure 2: Total and Differential Settlement (RMS, 2009.

It is also helpful to be aware that the settlement bowl in the longitudinal direction (i.e. direction of traffic) has the general shape shown in Figure 3, which may be idealised as a cosine curve. The tension zones which occur in the crest regions and the compression zone which occurs in the trough region, are also shown in Figure 3.

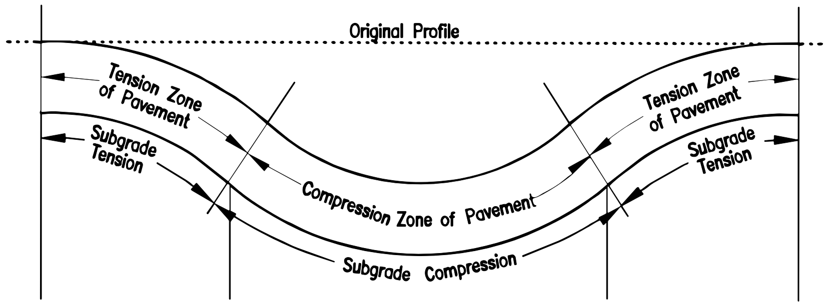

Figure 3: Idealised Settlement Bowl in Longitudinal Direction (i.e. direction of traffic) RMS, 2009

For the idealised cosine curve, the relationship between the maximum differential settlement, D, radius of curvature, R, and the half chord length, T, where 2T is the length of the settlement bowl, may be expressed by Equation 1 as follows:

$$D = \frac{2T^2}{\pi^2 R} \qquad [1]$$

In the transverse direction of the pavement, the settlement bowl is usually circular as shown in Figure 4 below, and the relationship between D, R, and T may be described by a circular arc, for small values of D compared to R, as shown in Equation 2.

$$D = \frac{T^2}{2R} \qquad [2]$$

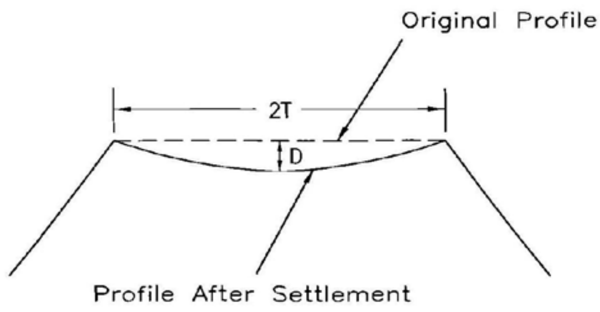

Figure 4: Idealised Settlement Bowl in Lateral Direction across Embankment (RMS, 2009)

However, these terms are not commonly used in current design practice, with design specifications generally calling for limits on change in grade, Δ , after pavement construction. The allowable value of Δ will depend on pavement types, and should be compatible with the minimum radius of curvature without causing pavement distress. Therefore, it is important to establish the definition of change in grade and its relationship with radius of curvature. Before doing so, it is also important to recognise that variations from the idealised curves of settlement bowls will exist as shown in Figure 5 for differential settlement in the longitudinal direction.

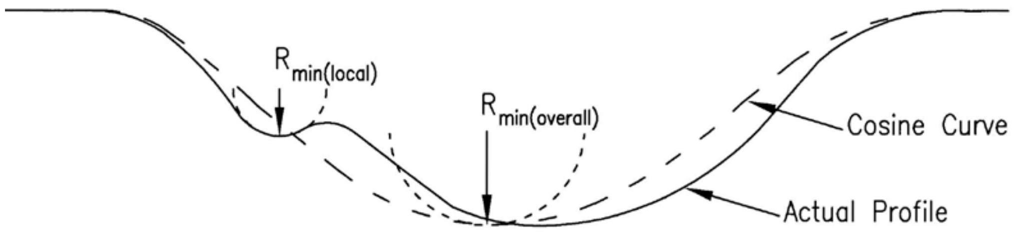

Figure 5: Settlement bowl showing the difference Between “Actual” $R_{min(local)}$ and “Theoretical” $R_{min(overall)}$ from fitted curve of cosine shape, based on the bowl length and the maximum differential settlement (RMS, 2009)

RMS (2009) suggest that $R_{min(overall)} = 2R_{min(local)}$ to be a reasonable assumption. At a local scale, the change in grade may be described by a circle as shown in Figure 6 regardless of the overall curve being a cosine curve or circle, so that the relationship between Δ, D and T may be described by Equation 3 as follows:

$$\Delta = \frac{2D}{T} \qquad [3]$$

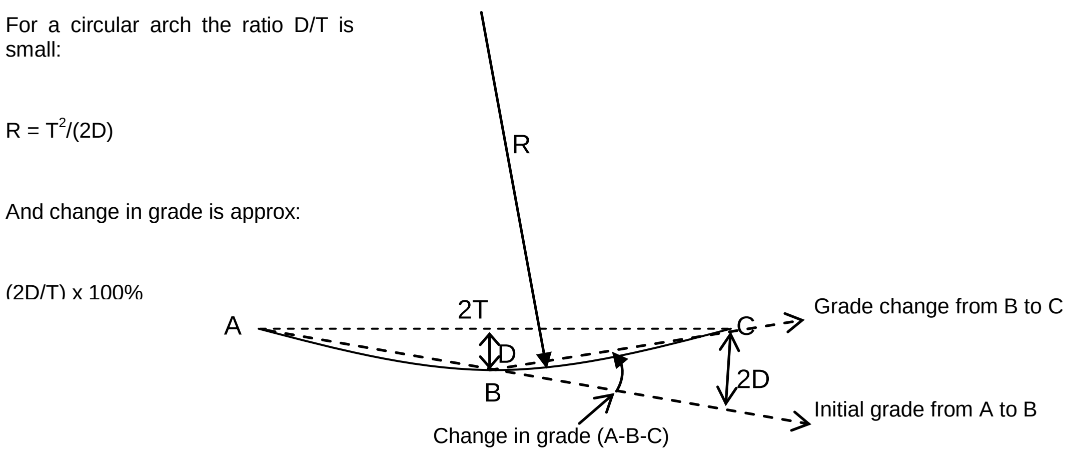

Figure 6: Relationship between change in grade, half chord length and radius of curvature

For example, if D = 0.02 m and T = 10 m, R would be 2,500 m and Δ would be 2D/T = 0.004 (or 0.4%).

Given that it is curvature that causes potential damage to pavements, it is important that design specification for change in grade not only specify Δ, but also stipulate the settlement bowl length or half chord length over which Δ is to be measured. In the above example, the design specification should be **"the change in grade should not be more than 0.4% measured over a 20 m length (or half chord length of 10 m) of any settlement profile"**, if the intention is to have a minimum radius of curvature of 2,500 m locally.

Later in this paper, typical design specification values of maximum change in grade will be compared with allowable radius of curvature values for the design of rigid pavements.

If the RMS (2009) suggestion of $R_{min(overall)} = 2R_{min(local)}$ is adopted, the relationship between change in grade, D and R may be written as Equations 4 and 5 as follows:

Longitudinal $$\Delta = \frac{2T}{\pi R_{min(local)}} \quad [4]$$

Lateral $$\Delta = \frac{T}{2R_{min(local)}} \quad [5]$$

3 PREVIOUS EXPERIENCE

In deep soft soil sites, large settlement due to construction of road embankments can be expected, and therefore pavement construction should ideally not take place until primary consolidation, under the design load, is complete. This may not be feasible in deep soft soil areas without installation of vertical drains. We understand from Queensland Main Roads that the low embankment along the Sunshine Motorway in Queensland is an example of a pavement constructed prior to completion of primary consolidation, designed to have long-term maintenance to deal with large post-construction settlements.

Beneath high embankments such as adjacent to bridge abutments, long-term post-construction creep settlement can be significant in deep soft soil sites even if primary consolidation is complete prior to pavement construction.

With respect to tolerable post-construction settlement, RMS has the following experience for concrete pavements:

- On Mittagong Bypass, localised settlement occurred on a skew angle and reached about 20 mm over a 15 m wave length before additional cracking became evident. This cracking became noticeably more serious at a value of 30 mm over 15 m. Anecdotal evidence which follows suggests that where differential settlement in excess of 100 mm occurs in a localised area, a concrete pavement surface is probably an incorrect choice.
- In several locations such as Brunswick Heads Bypass, Bulahdelah to Coolongolook and Karuah to Bulahdelah, good performance had occurred with plain concrete pavement on about 2-3 m fills on rock drainage blankets over paperbark swamps. The actual depth of soft soil was limited to a few metres and primary consolidation was easily achieved in the construction period.
- Intermediate depths of soft soils up to 14 m have mixed success with plain concrete pavements (PCP) on 2-3 m fills. There have been better results where about 2 years of fill settlement has been allowed prior to paving than using a shorter period of 12 months or less. Loading of soft soils still needs to be undertaken gradually and rotational shear failure avoided by using incremental loading with small plant. The problem on flood plains is that these often have filled former river channels with deeper soft soil which give greater settlement and lenses of sand, gravel and cobbles which dissipate pore pressures quickly at intermediate depths leading to an impression that primary consolidation has been achieved. The Yelgun to Chinderah section of the Pacific Highway Upgrade exhibits several examples of these problems.
- Soft soil depths in excess of 14 m usually have consolidation settlements of 1-2 m under fill embankments and even with great care, differential settlement at structures will require correction as was necessary at Leneghans Drive and other examples near Maitland and Port Macquarie. At Leneghans Drive a flexible pavement was adopted, and reinforcing geotextile, wick drains, lightweight fill (bottom ash) and pre-consolidation were all employed. An alternative is to construct CRCP at natural surface, as was the case with the Clybucca Stage 1 of the Pacific Highway Upgrade. However, the use of CRCP is only possible where an existing platform is available and flooding is allowed.
- Records of settlement and intervention provided by the RMS on a number of bridge approaches and culverts indicate total settlements at around 5 m from the bridge abutment were large ($\geq$ 200 mm) in a number of highway projects. AC correction had to be carried out within a few years of road completion and, in some

cases, (especially the Carlton Park Dam bridge along the Taree Bypass and the Windeyers Creek bridge along the Raymond Terrace Bypass) had three to four AC correction layers placed to between bridge completion in 1998 and June 2004.

- The recently completed Ballina Bypass is probably the most challenging highway project constructed on soft soils to date, where over 6 km of the 12.5 km route comprised extensive soft and highly compressible soils. Various ground treatments comprising preloading, surcharging with wick drains, deep soil mixing, stone columns, concrete column supported culverts, vacuum consolidation, and dynamic replacement were deployed to limit post-construction settlement limits to acceptable levels. On the northern section, the depth of soft soils is generally less than 10 m and PCP was adopted with a total post-construction settlement limit of 50 mm within the approach slab zone at bridge abutments and 100 mm elsewhere adopted for design. On the southern section, the depth of soft soils extends to 30 m in places, and it was not economical to apply the usual ground treatment for PCP to be adopted. At the southern approach to Emigrant Creek North, 6.5 m of settlement occurred during construction of the 5 m design height embankment. Vacuum consolidation was applied and a total of 14 m of fill was ultimately placed. A staged, flexible pavement was adopted with ground treatment limited to bridge approaches and embankments higher than 2.5 m to 3 m. Up to 0.5 m of post-construction settlement is expected at some places and a whole-of-life design philosophy was employed, with intervention measures costed and allowed for over the design life of the pavement. The northern section where PCP was adopted was open to traffic in March 2011. The southern section where flexible pavement was adopted was open to traffic in December 2011.

4 ALLOWABLE TOTAL AND DIFFERENTIAL SETTLEMENTS

4.1 GENERAL

Total settlement, if it is uniform, is only an issue if it affects flood immunity. Post-construction differential settlement on the other hand will affect pavement performance, ride quality, drainage, and could also affect road safety if it is excessive. However, it is likely that differential settlement will be higher with increasing total post-construction settlement due to variability of the ground, and it would be sensible to apply a design limit on total post-construction settlement as well as differential settlement.

The critical locations of differential settlement for highway projects are adjacent to rigidly supported structures such as bridges and culverts. Bridge approach embankments founded over soft ground may be divided into three broad zones as shown in Figure 7. Dimensions shown in Figure 7 for the structural and transition zones are typical but will obviously vary depending on the maximum embankment height at the bridge abutment and differential settlement criterion.

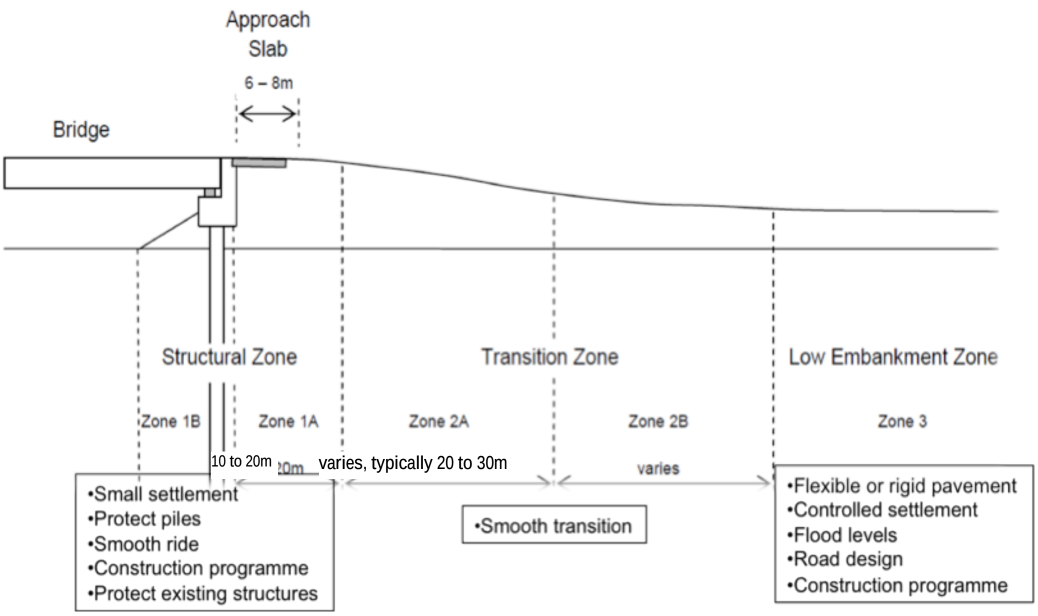

Figure 7: Embankment zoning for a typical road project

The structural zone is usually the most critical due to the fact that the abutments of structures are piled and will settle very little, and ground treatment in this zone must be accelerated to avoid delays to the structures which are usually on the critical path. The low embankment areas (less than 2.5 m to 3 m in height) generally have the longest lengths along the project, but these are less time critical and more post-construction settlement could be tolerated. However, the low embankments are also often complicated by the presence of flood culverts and the risk of settlement causing the finished surface to sink below design flood level. The transition zones lay between the above two zones in terms of criticality, but ground treatment within these zones must be carefully designed and constructed to allow a gradual increase in settlement such that post-construction differential settlement will be within tolerable limits in terms of smooth ride, adequate cross drainage, and road pavement or rail track performance requirements.

For flexible pavements, intervention to pavement distress may be catered for as part of the maintenance program in a whole of life design strategy, and higher total and differential settlement limits than rigid pavements can be adopted. Rigid pavements, on the other hand, are usually designed to have a minimum design life of 40 years with minimum maintenance. Repair to rigid pavements are also difficult and costly.

4.2 RIGID PAVEMENTS

The Roads and Maritime Services of New South Wales (RMS) have carried out extensive studies in developing a guide for design and performance of concrete pavements in areas of settlement (RMS 2009). The RMS guide is an extensive document and covers numerous types of pavements including Plain Concrete Pavement (PCP, reinforced PCP-R, doweled, PCP-D), Jointed Reinforced Concrete Pavement (JRCP), and Continuously Reinforced Concrete Pavement (CRCP). It mainly covers the design of concrete pavements for soft soils, but also touches on the subject of mining subsidence. The readers are therefore urged to read RMS (2009) to gain a comprehensive understanding of the background and design guidelines.

In this paper, we will only deal with tolerable settlements for concrete pavements constructed on soft ground, with ground treatment applied to limit the rate and extent of post-construction settlement (PCS) and differential settlements. Rigid pavements are unlikely to be suitable for areas of mine subsidence where large differential settlements and strains may be expected.

4.2.1 Settlement Induced Stress and Importance of Settlement Rate

In general, concrete pavements are not suited to situations of large and rapid settlements such as areas susceptible to mining subsidence, and therefore we will restrict our discussions to soft soils on which some form of ground treatment (e.g. preloading or surcharging) will be performed so that the residual settlement after pavement construction will occur slowly and be limited to manageable values.

Figure 8 shows examples of fast and slow rates of settlement, where the maximum differential settlement at 40 years is the same. The settlement rate may be described as “slow” if the maximum depth of differential settlement over a 3 year period since paving is no more than half the settlement over 40 years.

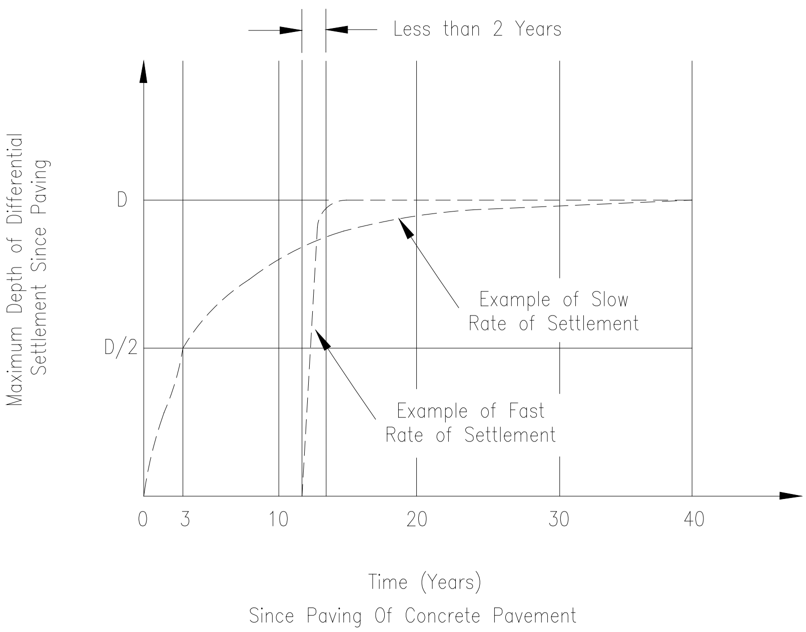

Figure 8 - Examples of fast and slow rates of settlement (RMS, 2009)

The rate of settlement is important because settlement induced stress in the pavement is directly proportional to the elastic modulus of the pavement, and creep relaxation in the pavement will reduce the concrete modulus which will in turn reduce the settlement stress. Therefore, a slow rate of settlement is important following pavement construction. The settlement stress may be expressed by Equation 6 as follows:

$$Settlement\ Stress = \frac{t_b E_b}{2R_{\min(local)}(1-v^2)CR_b} \qquad [6]$$

where:

t_b = thickness of the concrete base
E_b= elastic modulus of the concrete base at 28 days
v = Poisson's ratio of the concrete base
CR_b= creep ratio of the concrete base (a modulus ratio which depends on creep with time)

The ratio CR_b ranges from 1.0 in the first year, to typically more than 2 from year 3 onwards. Where the rate of settlement is slow, more differential settlement can be tolerated because of the benefits due to creep relaxation of the concrete.

4.2.2 Tolerable Total Settlement

Although uniform total settlement should not cause pavement distress, it is unlikely that total settlement would occur without some form of differential settlement. The RMS (2009) guide suggested that the maximum differential settlement, D shown in Figure 2, be assumed to be up to 2/3 of the total settlement. Also, RMS (2009) indicated that the length of the settlement bowl for PCP be limited to 40 m unless a number of other criteria are considered to assess whether a concrete pavement can be used and if so what pavement design is necessary.

Immediately adjacent to rigidly supported structures, the allowable total settlement in 40 years is usually set at about 50 mm at the end of the approach slab (see Figure 7). In long stretches of embankment well away from the structural and transition zones, a total post construction settlement limit of 100 mm for PCP has been used as the design specification for most Pacific Highway Upgrade projects in the last 15 or so years. Sections of the Pacific Highway have experienced long wave length total settlements of over 200 mm over a period of ten years, which have so far not caused pavement distress. However, as pavement distress is a function of pavement deformation, fatigue due to traffic loading as well as temperature effects, the combined effect of settlement stress, traffic loading and variations in temperature will not necessarily be known for many more years over the design life of the pavement.

4.2.3 Tolerable Differential Settlement for Ride Quality

The relationship between vertical vehicle acceleration, a_v, and the radius of curvature (for a circular arc) is shown in Equation 7 below:

$$a_v = \frac{V_T^2}{R} \qquad [7]$$

where:

V_T = tangential velocity on curve = vehicle speed (m/sec)
R = radius of curvature (m)

The choice of the maximum vertical acceleration, a_{vmax}, is somewhat subjective. The RMS Design Guide (RMS 1998) suggests a limit of 0.05g (about 0.5 m/sec^2) for high standard roads, to 0.1g (about 1 m/sec^2) for low standard roads or at intersections. For 110 km/hr speed, the above limits correspond to minimum radius of curvature of approximately 1860 m and 930 m for high standard and low standard roads respectively.

For 110 km/hr speed on a high standard road, adopting a design value of a_{vmax} = 0.6m/sec^2 would give a minimum radius of curvature of 1560 m. RMS (2009) adopts a $R_{min(local)}$ value of 850 m for light traffic and slow rate of settlement, but also allows this minimum radius of curvature to be adopted for medium and heavy traffic provided other pavement design criteria are satisfied.

4.2.4 Tolerable Differential Settlement for Structural Integrity of Pavement

RMS (2009) provides a detailed framework including flowcharts and tables for determining the tolerable differential settlement and pavement thickness in order to maintain pavement integrity over the pavement design life. In brief, the RMS (2009) framework is as follows:

1. An initial assessment is made for PCP or PCP-R having minimum modulus of rupture (MR) of 4.5 MPa and minimum thickness of 225 mm for the base concrete, a minimum subbase concrete thickness of 125 mm having minimum compressive strength of 20 MPa, and limiting the length of the settlement bowl to 40 m for PCP and 55 m for PCP-R.

2. $R_{min(local)}$ values of 10,000 m (fast rate of settlement) and 5,000 m (slow rate of settlement) are adopted for the initial assessment; allowable differential settlements are calculated using these values and the total tolerable settlement in the longitudinal direction is assumed to be 1.5 times the maximum differential settlement.
3. If the anticipated total and differential settlement are less than those stipulated using the above $R_{min(local)}$ values, design of the PCP may then be carried out using conventional design practice (i.e. no settlement induced stress need to be considered).
4. If the above condition is not met, PCP and PCP-R are deemed to be not suitable and other types of concrete pavements such as PCP-D, JRCP and CRCP would need to be considered.
5. For PCP-D, JRCP and CRCP concrete pavements, the minimum tolerable $R_{min(local)}$ values are reduced to 2,500m for fast rate of settlement and 850 m for slow rate of settlement for light traffic (i.e. typically less than one year of highway traffic). For medium and heavy traffic, $R_{min(local)}$ values will need to be higher than 2,500 m and 850 m for "slow" and "fast" rate of settlement, the pavement thickness may also need to be increased and is the largest of the following:
   a. B_e = base concrete thickness to satisfy the erosion distress from traffic (as in conventional design)
   b. B_f = base concrete thickness to satisfy the fatigue distress from traffic (as in conventional design)
   c. B_{fs} = base concrete thickness to satisfy fatigue distress from traffic and bending stresses, from self-weight due to settlement
   d. B_{st} = base concrete thickness needed to ensure the base after experiencing bending stresses, from self-weight, due to settlement, maintains the same capacity for stresses from heavy axle groups in conjunction with positive temperature differentials, that it had prior to settlement.

Combining the above guide with ride quality considerations discussed in Section 4.2.3, it would seem reasonable to assume that for concrete pavements for highway projects, $R_{min(local)}$ would need to satisfy the following, provided that post-construction settlement will fall within the "slow" category described in Section 4.2.1 :

- $R_{min(local)}$ > 1,600 m for ride comfort (assuming a_{vmax} = 0.6 m/sec^2 is acceptable at a design speed of 110 km/hr)
- $R_{min(local)}$ > 5,000 m for PCP or PCP-R
- $R_{min(local)}$ > 2,500 m for PCP-D, JRCP and CRCP

The relationship for D, T and the above $R_{min(local)}$ assuming localised differential settlement bowl may be described as a circular arc (see Figure 6) , is presented in Figure 9.

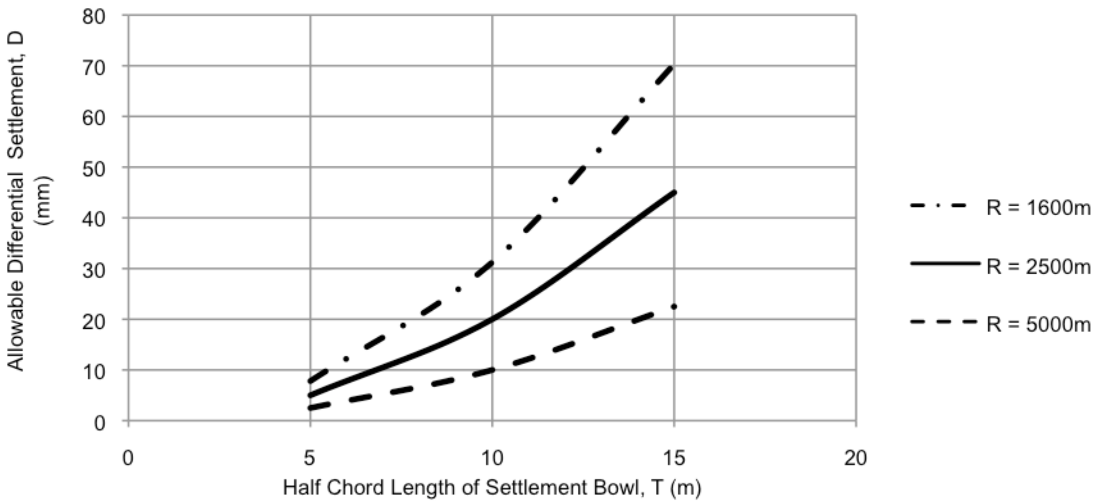

Figure 9: Relationship between D, T & $R_{min(local)}$ for localised settlement bowl described by circular arc.

In addition, where the expected $R_{min(local)}$ is less than 5,000 m, an increased pavement thickness from the larger of (B_e , B_f) to the larger of (B_{fs} , B_{st}) may be required.

The values B_{fs} and B_{st} may be assessed as follows:

(a) Assessment of minimum base thickness B_{fs}

The assessment of minimum base thickness B_{fs} to satisfy fatigue distress from traffic and bending stresses due to settlement requires a time marching process taking into account the settlement history and stress relaxation. RMS (2009) has developed a Design Thickness for Settlement Spreadsheet for this computation.

As an example to illustrate the process involved, a simple case of a one off settlement is provided below. For a one off settlement, the settlement stress at this particular time is as described in Equation 8. The thickness, t_b must be such that for each axle group:

$$\frac{Settlement\ Stress}{Modulus\ of\ Rupture} = \frac{Reduction\ in\ Traffic\ Stress\ due\ to\ increase\ in\ thickness\ from\ B_f\ to\ t_b}{Modulus\ of\ Rupture} \quad [8]$$

An iterative approach is adopted to determine the value of t_b as illustrated in Figure 10. In this figure, point A_1 is the stress state before any settlement for base thickness of B_f , ie traffic stress = S_e (for the particular axle group and standard load) and point B_1 is the stress state for B_f after including bending stresses from settlement. As t_b is increased by an increment of thickness from B_f , A_2 is the new stress state for this increased thickness after settlement. The process is repeated until finally the point B_5 is reached. At this last thickness, the stress state has the same fatigue life as B_f without settlement which means the thickness for A_5 and B_5 is B_f. The readers should refer to RMS (2009) for further details of this approach including the calculation of equivalent S_e which gives the same fatigue life for the trial thickness for no settlement stress.

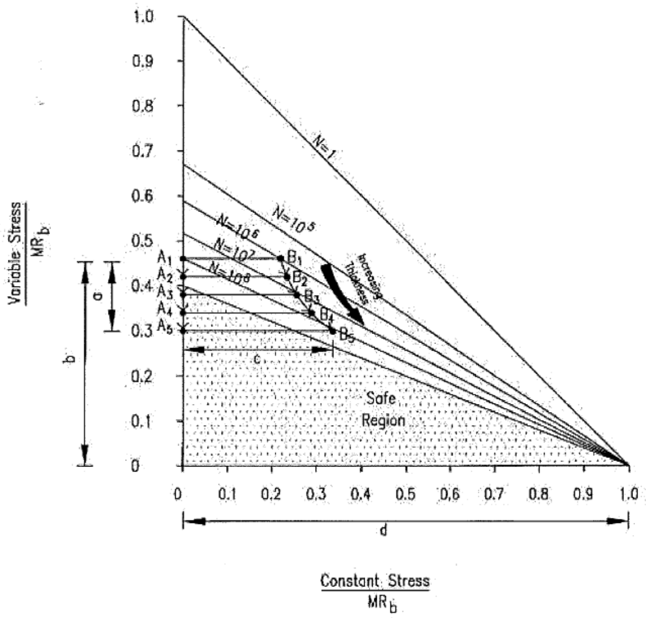

Figure 10: Effect of increasing concrete base thickness on the stress state due to a given traffic load and settlement situation at a particular time (RMS, 2009)

(b) Assessment of minimum base thickness B_{st}

To determine B_{st} needed such that the concrete base after experiencing settlement stresses maintains the same capacity for stresses from heavy axle groups in conjunction with positive temperature differentials, the effect of change in curvature from settlement over time, the change in bending stresses from stress relaxation over time, and temperature differential need to be taken into account. According to RMS (2009), the minimum thickness B_{st} , for each axle group, is required to satisfy the following equation:

$$\frac{1-\left(Z\ for\ \frac{B_{st}}{MR_b}\right)-\frac{Settlement\ Stress}{MR_b}}{S_e for\ B_{st}/MR_b} \geq \frac{1-\left(Z\ for\ \frac{B_f}{MR_b}\right)}{S_e for\ B_f/MR_b} \quad [9]$$

where Z – tensile stress due to positive temperature differentials, using a nominated value, or using a formula related to base thickness, and other parameters, such as AASHTO (1998).

Once the minimum value of B_{st} is obtained for each axle group, the larger of the computed values is the B_{st}. So long as each year uses less than 100% of fatigue capacity then the pavement is considered satisfactory, where the value for B_f for each year is determined on the basis of the traffic for that year.

In the simplistic case where the settlement was just a one off, and where only one particular year is examined, the value of B_{st} would simply need to satisfy the following equations:

$$\frac{\left[1-\left(Z\ for\ \frac{B_{st}}{MR_b}\right)-\frac{[Settlement\ Stress]}{MR_b}\right]\left[\frac{S_e for\ B_f}{MR_b}\right]}{\left[S_e for\ \frac{B_{st}}{MR_b}\right]\left[1-\left(Z\ for\ \frac{B_f}{MR_b}\right)\right]} \geq 1 \qquad [10]$$

$$\frac{\left[1-\left(Z\ for\ \frac{B_{st}}{MR_b}\right)-\frac{B_{st}E_b}{2R_{\min(local)(1-v^2)CR_b}}\right]\left[\frac{S_e for\ B_f}{MR_b}\right]}{\left[S_e for\ \frac{B_{st}}{MR_b}\right]\left[1-\left(Z\ for\ \frac{B_f}{MR_b}\right)\right]} \geq 1 \qquad [11]$$

The above are simplified guidance only, and we stress again that the readers should consult RMS (2009) for further understanding of the differential settlement issues for the design of concrete pavements and more detailed guidance on design procedures.

4.3 FLEXIBLE PAVEMENTS

Where a flexible pavement with thin AC surface is to be adopted greater total and differential settlements may be adopted because flexible pavements attract lower settlement stress, and the ability to perform remedial works more readily than for rigid pavements. Kay *et al.* (2011) indicates that the long-term Young's modulus of AC may be in the range of 10 MPa to 15 MPa for slow rates of strain and hence slow settlement when creep relaxation is taken into account. These are 2 orders of magnitude lower than the resilient modulus of AC under traffic loading conditions and more than 3 orders of magnitude lower than that for concrete pavements.

Typical values of total post-construction settlement limits specified for flexible pavements for highway projects range from about 200 mm to 300 mm generally, but as in the case of Ballina Bypass, higher values (> 500 mm in some cases) have been adopted away from rigidly supported structures on the basis that periodic maintenance has been included as part of the whole-of-life design strategy. Within the bridge approach slab zone, however, a limit on total settlement of 50 mm is also the normal design approach to maintain ride quality except for unusual circumstance.

With respect to differential settlement, ride quality will probably dictate, and therefore a minimum radius of curvature of 1,600 m would therefore be applicable as discussed in Section 4.2.3. However, this limit could be considered for a shorter time period than for concrete pavements because of the ability to perform minor, localised shape corrections as part of the normal maintenance regime for flexible pavements. As such, the minimum radius of curvature of 1,600m may be considered an overall value, and hence the adoption of $R_{min(local)} \geq 800$ m would appear reasonable for flexible pavements.

RMS has experience in the performance of composite pavements (flexible base with stabilised subbase) in a mining environment (Kay *et al.,* 2011). For these pavements the stabilised subbase behaves in a similar fashion to a rigid pavement. In this case it is compressive pavement strains associated with the subsidence bowl or subsidence wave that is of concern, rather than the magnitude of settlement or differential settlement. These compressive strains over pavement lengths of up to 500 m can lead to compression failure and stepping of the pavement. The potential for stepping is managed in part by cutting slots through the subbase to relieve these compressive strains.

5 DESIGN PRACTICE VERSUS THEORETICAL LIMITS

For situations such as mine subsidence areas, the potential settlement trough is large and some prediction of the extent and shape of the settlement bowl is possible, and hence the potential differential settlement can be assessed and compared with the theoretical guideline limits discussed above. In such areas, the use of concrete pavements may not be suitable, and other forms of pavement with intervention strategy should be considered.

For pavements constructed on soft ground, however, it is quite difficult to use minimum radius of curvature for design purposes due to the difficulties associated with predicting small post-construction total and differential settlements. This is particularly the case with concrete pavements. The radius of curvature, therefore, may be better used as a measure of performance after the pavement is put into service and when many years of monitoring data become available.

In practice, project specifications usually call for limits on change in grade over the design life of the pavement. For example, commonly adopted limits on change in grade are:

- 0.3% in 40 years for concrete pavements
- 0.5% in 20 years for flexible pavements

As discussed in Section 2, for design, it is necessary to nominate the chord length of the settlement bowl, 2T, (or the half chord length, T) for which these changes in grade are applied. However when assessing performance the half chord length should be selected based on the actual shape of the settlement bowl.

However, the application of these limits on change in grade or minimum radius of curvature over the approach slab zone is not necessary as the approach slab is reinforced and designed to be supported between the bridge abutment and the anchor block at the other end of the slab. For a typically accepted 50 mm post-construction settlement at the far end of a 6 m approach slab located on an approach embankment on soft ground, the change in grade would be about 1.7% in this short section. The more important section of the pavement for the limits on post-construction differential settlement to be applied is the transition zone behind the approach slab.

The design of ground treatment is usually carried out in such a fashion that the predicted post-construction settlement would vary linearly (theoretical design intention) from the expected value at the end of the approach slab of say 50 mm, to the maximum allowable settlement of say 100 mm at the end of the transition zone. For example, if the transition zone behind the approach slab is 30 m, then the slope of the settled ground surface would be {(0.1-0.05)/30} x 100 = 0.17% from the as-constructed pavement profile for this example. However, this should not be mistaken as the change in grade because a linear slope has no change in grade. A change in grade could occur at the beginning and ends of the transition zone, or within and beyond the transition zone due to the post-construction settlement occurring non-linearly and different to that predicted due to variations in soil profile (e.g. unexpected shape/depth of palaeochannel and/or soil properties). Furthermore, due to more extensive ground treatment usually applied behind the bridge abutment, the end of the approach slab may not settle as much as predicted, giving rise to a greater differential settlement in the transition zone. These effects are illustrated in Figure 11 for a case of a 30 m transition zone. In this example, the design was based on a variation of post-construction settlement (PCS) from 50mm to 100mm over a 30 m transition zone. As discussed above, the differential settlement within the 6 m approach slab zone may be disregarded. Figure 11 shows that if the actual settlement profile at the end of the pavement life is as shown in the solid line, then the localised differential settlements in the two high curvature areas would produce an actual change in grade of 0.4% and 0.3%.

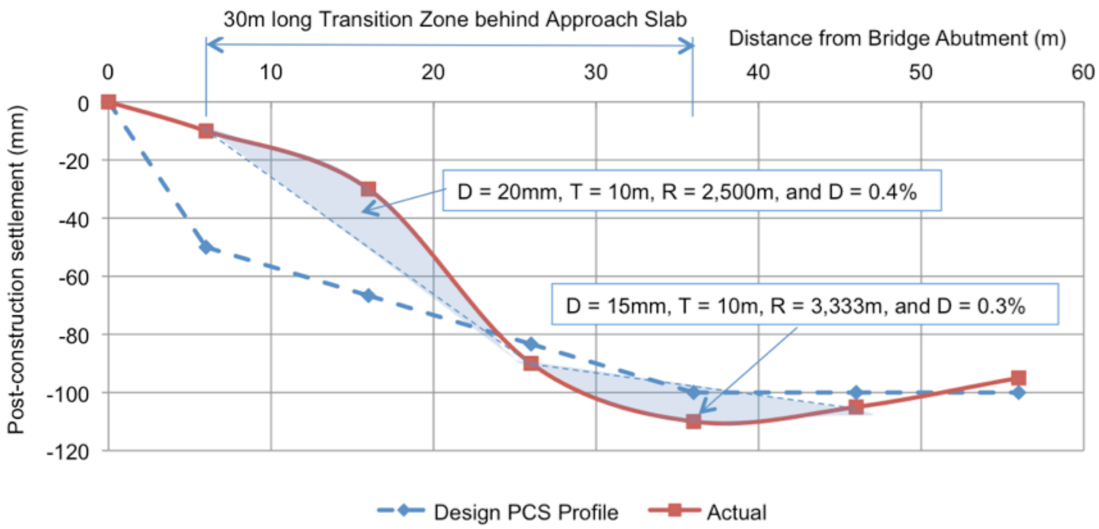

Figure 11 - Potential variations in differential settlement from Design Profile.

The above example highlights the importance for the designer to consider potential variations between design and actual differential settlement (which is difficult to predict), and not to confuse design change in PCS with potential change in grade by allowing a sufficient length of transition zone. It must be borne in mind that the greater the ratio of difference in design settlement over a given length, the greater risk of there being differential settlement exceeding the design limits.

6 CONCLUSION

The key findings of this paper are summarised below:

1. The impact on pavement is governed by differential rather than total settlement, although it must be expected that the greater the post-construction settlement, the greater the risk that differential settlement would occur.
2. To enable stress relaxation of the pavement to occur to reduce distress to the pavements, it is important that sufficient ground treatment be carried out such that post-construction settlement (PCS) would be of the "slow" type (i.e. less than 50% of the PCS would occur within the first 3 years of pavement construction).
3. It would seem reasonable to assume that for concrete pavements in highway projects, $R_{min(local)}$ would need to satisfy the following, provided that post-construction settlement will fall within the "slow" category described in Section 4.2.1:
   - $R_{min(local)}$ > 1,600 m for ride comfort (assuming a_{vmax} = 0.6m/sec^2 is acceptable at a design speed of 110 km/hr)
   - $R_{min(local)}$ > 5,000 m for PCP or PCP-R
   - $R_{min(local)}$ > 2,500 m for PCP-D, JRCP and CRCP
4. For certain conditions, the pavement thickness may need to be increased to account for settlement induced stresses, and a very brief summary of the approach suggested in RMS (2009) to assess the required thickness increase is summarised in this paper. The readers should refer to RMS (2009) for further details.
5. Flexible pavements should be adopted if the differential settlement criteria suggested above cannot be met.
6. For practical design purposes, the use of "change in grade" may be adopted provided the half chord length of the localised settlement bowl is also specified. The following values would appear to be reasonable specification values:
   - 0.3% in 40 years for concrete pavements measured over 10 m half chord length
   - 0.5% in 20 years for flexible pavements measured over 10 m half chord length
7. Designers should not confuse design change in PCS with potential "change in grade" as illustrated in Figure 11.
8. It is importance for designers to consider potential variations between design and actual differential settlement (which is difficult to predict) and a sufficient length of transition zone should be provided in the design to allow for uncertainties.

Other issues such as impact of post-construction settlement on adjacent structures and drainage, which have not been discussed in this paper, must also be considered in design of ground treatment of highway projects on soft ground.

7 REFERENCES

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