IMPROVING TRAFFIC LOAD OUTCOMES FOR IMPACT ASSESSMENT OF EXISTING PIPES UNDER NEW INFRASTRUCTURE

Sarath Somasundaram[1], Peter J. Waddell[2] and Thu Minh Le[3]
[1]Principal Engineer, [2]Technical Director, [3]Geotechnical Engineer
AECOM, 420 George Street, NSW 2000, Australia

ABSTRACT

Infrastructure upgrades often encounter buried pipes that are impacted by traffic loading. Depending on the outcome of impact assessment, pipe diversion or protection works are often required. Given the significant constraints in working space, working hours and traffic management, pipe diversion or protection works often result in significant impacts on project schedule and cost.

An integral part of impact assessment is the evaluation of vertical stress transferred to pipe level from traffic loads. Australian Standards such as AS 5100.2(2017) and AS/NZ 3725(2007) provide guidelines on stress distributions under traffic load, treating the ground as a "uniform elastic soil mass". Given the economic implications, the authors consider that a multi-layered approach offers benefits compared to this approach by accounting for greater vertical stress dissipation resulting from overlying stiffer pavement layers.

Multi-layered stress analyses are routinely carried out by pavement engineers to evaluate stresses within pavement layers and the pavement subgrade. However, layered modelling techniques are often not applied in impact assessment of pipes buried under pavements. This paper presents multi-layered stress analysis for a number of load cases including both road and light rail loadings. Typical pavement configurations have been considered and a series of plots have been developed giving vertical stress distributions under these conditions. These vertical stress distributions are compared with those resulting from the AS 5100.2(2017) and AS/NZ 3725(2007) approaches to demonstrate the potential benefits of adopting multi-layered stress distributions.

1 INTRODUCTION

Infrastructure development works such as new roads, railways, road widening/upgrade and light rail along existing road corridors often increase loading on existing buried pipes. In addition, the impact assessment is often carried out under technical requirements that are more stringent than those considered when the pipes were installed.

An objective assessment of impacts due to these additional loads requires a good grasp of fundamentals across a number of disciplines such as structural, geotechnical, pavement and hydraulic engineering. This paper presents:

- A brief overview of approaches to the pipe structural design process,
- Discussion of key factors that impact structural performance of buried pipes,
- Discussion on guidelines provided in relevant Australian Standards with respect to traffic load assessment,
- An overview of multi-layered stress analysis approach,
- Comparison between and stress assessments based on Australian Standard guidelines and multi-layer stress analyses, and
- Further considerations relevant to improving traffic load assessment outcomes.

2 PIPE STRUCTURAL DESIGN APPROACHES

Often geotechnical engineers play a key role in impact assessment of existing pipes under new traffic load. Having an appreciation of structural pipe design considerations is beneficial in such circumstances. Therefore, a brief discussion of structural pipe design process is presented below.

Pipes are classified as "rigid" or "flexible" based on how they resist vertical load. Rigid pipes such as reinforced concrete pipes and vitrified clay pipes rely primarily on pipe material strength to resist loads without crushing. Flexible pipes made from materials such as steel and plastics such as PVC, GRP, and HDPE rely primarily on external soil support to resist deformation.

Design of rigid pipes in Australia is primarily governed by the following Australian Standards:

- AS/NZS 3725 "Design for installation of buried concrete pipes"
- AS/NZS 4058 "Precast concrete pipes (pressure and non-pressure)"
- AS 4060-1992 "Loads on buried vitrified clay pipes"

- AS 1741-1991 “Vitrified clay pipes and fittings with flexible joints-sewer quality”

Key factors affect the performance of a rigid pipe include crushing strength, load on top of the pipe and its bedding conditions. Figure 1 presents the steps involved in structural design of rigid pipes.

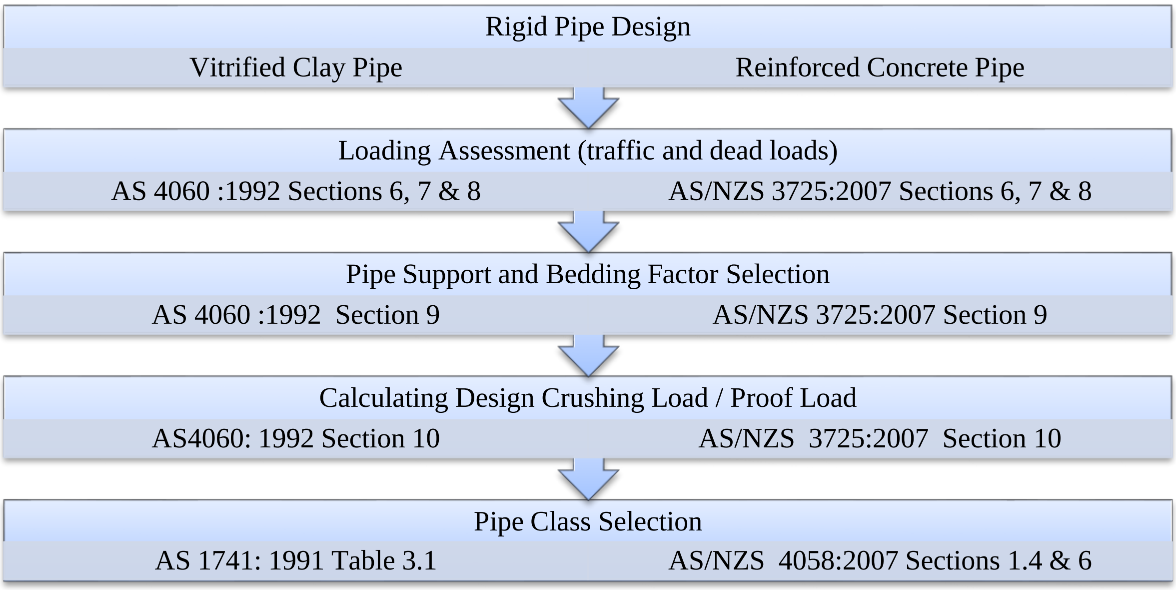


Figure 1**:** Overview of rigid pipe design process

Optimising traffic load surcharges and establishing the pipe class are key prerequisites for an objective impact assessment of rigid pipes.

Design of flexible pipes in Australia is primarily governed by AS/NZS 2566.1:1998 “Buried flexible pipelines”. Key factors affect the performance of a flexible pipe include stiffness of the surrounding soil, load on top of the pipe and its bedding conditions. Figure 2 presents the steps involved in structural design of flexible pipes.

Optimising traffic load surcharges, establishing pipe strength / stiffness and establishing the stiffness of side support, bedding and subgrade are key prerequisites for an objective impact assessment of flexible pipes.

In addition to the above design considerations, the following aspects may also need assessment, depending on project circumstances:

- Internal pressure of pressure pipes
- Allowable pipe joint rotation and differential settlement tolerance, if pipes are founded on settling ground.
- Potential changes in flow gradient due to settlement; for gravity flow pipes.

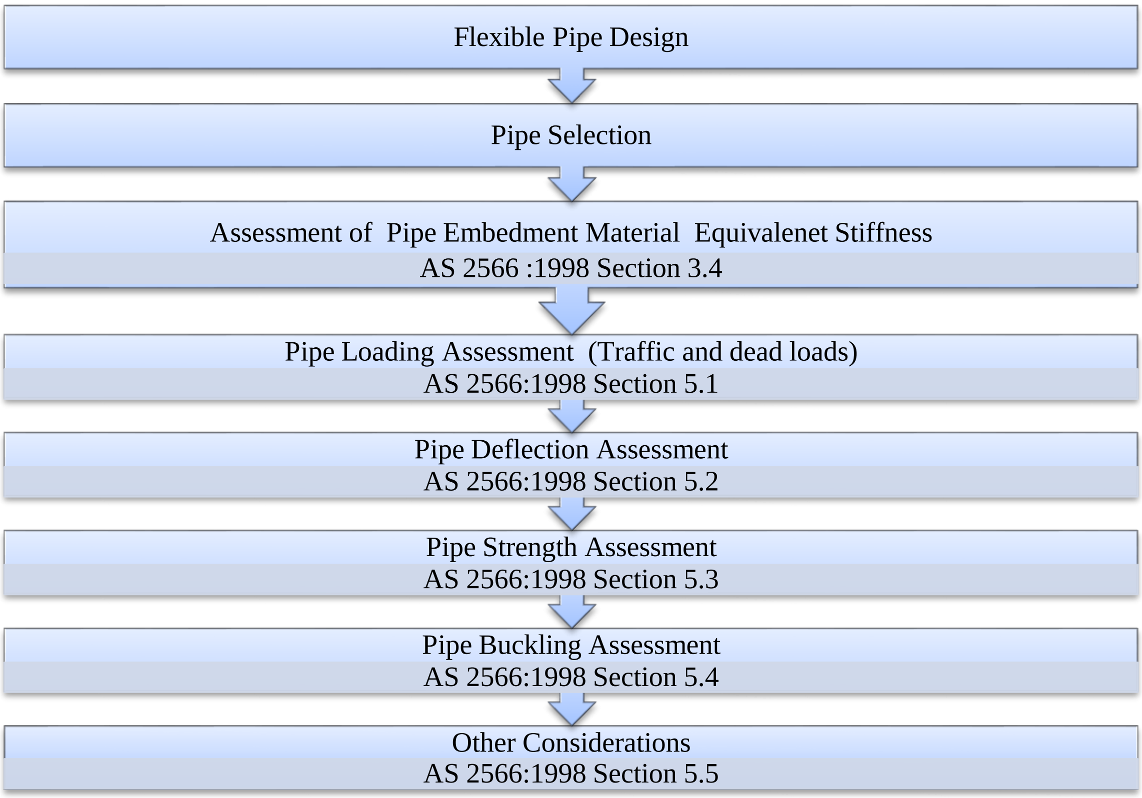


Figure 2: Brief Overview of Flexible Pipe Design Process

3 TRAFFIC LOAD ANALYSIS APPROACHES

3.1 TRAFFIC LOAD MODELS

Most Australian pipe design standards cross reference AS 5100.2 “Design Loads” for traffic load models to be considered in pipe assessments. Section 7 of AS 5100.2(2017) provides the following traffic load models for the design of highway structures:

- W80 Single wheel load – that models 80 kN load over a contact area of 0.4 m x 0.25 m,
- A160 Axle load – which models an axle with two W80 wheel loadings at 2m centre distance,
- M1600 Moving load – which models moving traffic via a series of 120 kN x 3 “Tri-axle” loads and a 6 kN/m line load (see Figure 7.2.4 of AS 5100.2:2017),
- S1600 Traffic load – which models stationary traffic via a series of 80 kN x 3 “Tri-axle” loads and a 24 kN/m line load (see Figure 7.2.5 of AS 5100.2:2017),
- HLP 320 load – which models 16 x 200 kN axle loadings at 1.8 m centres (see Figure 7.3 of AS 5100.2:2017), and
- HLP 400 load – which models 16 x 250 kN axle loadings at 1.8 m centres (see Figure 7.3 of AS 5100.2:2017).

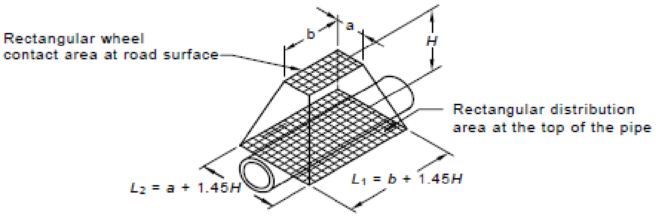
In addition to traffic load models, AS 5100.2(2017) also provides guidance on aspects such as dynamic load allowance, lane factors for multiple lane-roads and fatigue design loads, which should be considered in pipe impact assessments, where applicable.

To illustrate the concepts discussed in this paper, analyses were carried out using W80 Single wheel load (which is typically more critical for shallow pipes) and M1600 Moving load over two lanes (which is typically more critical for deeper pipes).

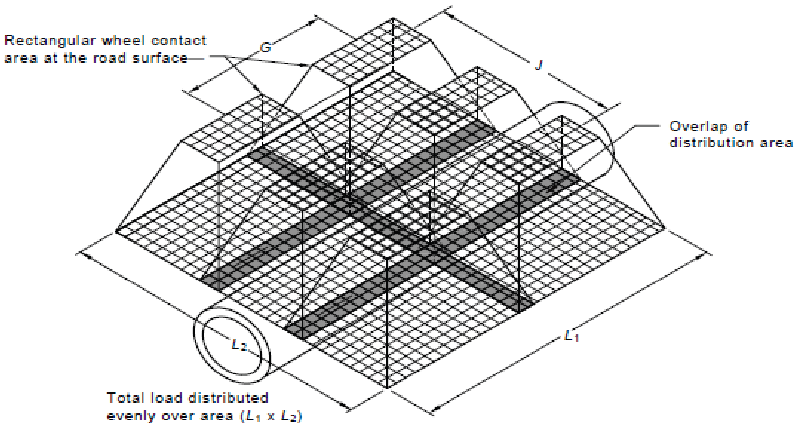
The current version of AS 5100.2(2017) includes a section on light rail loads (Section 9.3). In view of the prevalence of light rail projects in the current Australian construction sector, this light rail load model is also considered in this paper.

3.2 AS/NZS 3725 TRAFFIC LOAD DISTRIBUTION APPROACH

The AS/NZS 3725 approach to traffic load associated stress distribution involves a trapezoidal distribution as shown in Figure 3. Approaches in AS 2566 and AS 4060 are similar.



(a) Single wheel load distribution for height of fill ⩾ 0.4 m



(b) Multiple wheel load distribution for height of fill ⩾ 0.4 m

Figure 3: Trapezoidal distributions assumed in AS/NZS 3725

(Figure 9 © Standards Australia Limited. Copied by AECOM Pty Ltd with the permission of Standards Australia under Licence 1707-c113 from AS 3725:2007)

AS/NZS 3725 also considers a dynamic allowance of 0.4 and 0.3 for W80 and M1600 load cases respectively. Consistent with guidance provided AS/NZS 3725 supplement and AS 5100.2(2017), these values are assumed to be linearly reducing with depth between ground level and 2 m depth below pavement level. A lane distribution factor of 0.8 is also considered for the M1600 Moving load, a multiple lane model.

3.3 AS 5100.2 APPROACH

In addition to providing traffic load models, Section 7.12 of AS 5100.2 (2017) suggests that the stress at a depth of “h” be taken as a wheel load distributed over an area of:

{a+100 mm+1.2 (h-200 mm)} x {b+100 mm+1.2 (h-200 mm)};

Where ‘a’ and ‘b’ are dimensions of an idealised wheel contact area and “h” is depth (>200 mm)

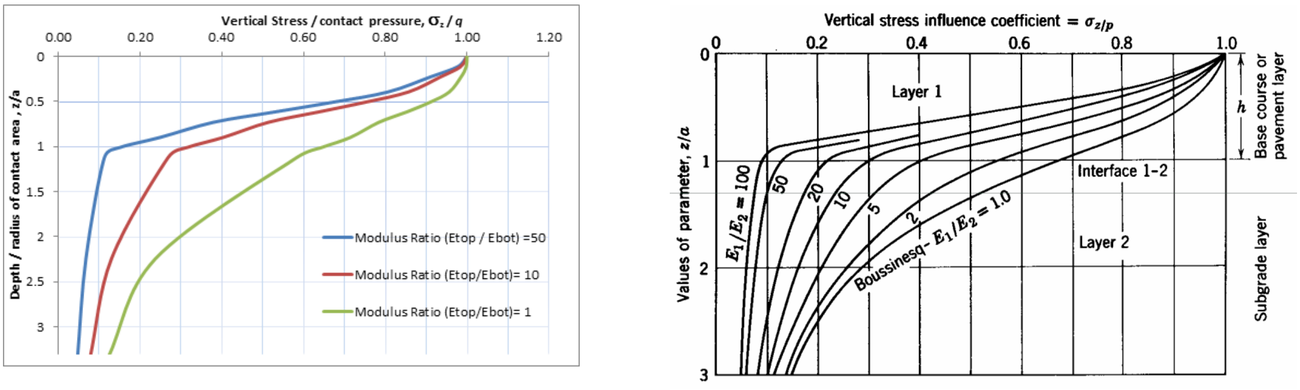
AS 5100.2(2017) also suggests that where distribution areas from several wheel loads overlap, the total load may be considered to be evenly distributed on the surface over the total area of distribution.

4 MULTILAYER STRESS ANALYSIS

The approaches discussed in Sections 3.2 and 3.3 inherently assume that ground is a homogeneous, isotropic, elastic, semi-infinite solid mass. A multi-layer stress analysis, on the other hand, accounts for the effects of differences in stiffness of layers within a profile on stress distribution. This is particularly useful where pipes are overlain by relatively stiff pavement layers.

Multi-layer stress analysis theories have been in existence for a long time (Burmister, 1945; Huang, 1967; Wardle, 1977) and have routinely been used in pavement analysis and design. While commercially available geotechnical finite element programs are capable of carrying out multilayer stress analyses, they either involve modelling limitations (e.g. 2 dimensional “plane strain” finite element analysis) or a too complex for the purpose of routine pipe impact assessments (e.g. 3D finite element analysis).

In this paper, the finite layer program FLEA (**F**inite **L**ayer **E**lastic **A**nalysis, Centre for Geotechnical Research, The University of Sydney) is used to analyse multi-layer stress distributions. FLEA allows analysis of horizontally layered elastic materials subjected to circular, strip and rectangular loadings. It also allows analysis of incompressible (i.e. Poisson’s ratio = 0.5) and cross-antistrophic materials. Theoretical basis for this finite layer, elastic analysis approach together with governing equations is presented in Small and Booker (1986). To validate the FLEA results, Burmister’s influence chart (Burmister, 1958) for a two-layered, homogeneous, isotropic, linearly elastic, weightless, semi-infinite area were compared to FLEA results. Figure 4 shows close agreement between FLEA and the influence chart solutions for the case where the thickness of the top layer is equal to the radius of the circular contact area. Stresses in the underlying layer reduce significantly as the modulus ratio between the stiffer top layer and the bottom layer increases.



(a) (b)

Figure 4: Vertical stress distribution in a two-layer system a) FLEA result and b) Burmister (1958)

5 COMPARISON OF RESULTS

Stress distributions from FLEA analyses are compared to AS/NZS 3725 and AS 5100.2 stress distributions for two load configurations presented in AS 5100.2(2017), in combination with a number of pavement profiles, as discussed below.

5.1 W80 SINGLE WHEEL LOAD

The W80 Single wheel load models a single 80 kN wheel load uniformly distributed over a contact area of 400 mm x 250 mm. Stress distributions for three typical pavement types as presented in Tables 1 to 3 below have been assessed.

Table 1: Granular Pavement with Thin Asphaltic Concrete Surface

Layer No.	Material	Thickness (mm)	Young’s Modulus (MPa)
Layer 1	Asphaltic concrete wearing course	50	2,000
Layer 2	DGB base course	250	350
Layer 3	DGS subbase	250	200
Layer 4	Select Material Zone	300	150
Layer 5	Subgrade	Infinite	30

Table 2: Full Depth Asphalt Pavement

Layer No.	Material	Thickness (mm)	Young’s Modulus (MPa)
Layer 1	Asphaltic concrete	200	2,000
Layer 2	Lean mix concrete base course	200	700
Layer 3	Select Material Zone	300	150
Layer 4	Subgrade	Infinite	30

Table 3: Reinforced Concrete Pavement

Layer No.	Material	Thickness (mm)	Young’s Modulus (MPa)
Layer 1	Reinforced concrete	200	20,000
Layer 2	Lean mix concrete base course	200	700
Layer 3	Select Material Zone	300	150
Layer 4	Subgrade	Infinite	30

Subgrade modulus was selected to represent an equivalent modulus when compacted fill is used in bedding and side zones as defined in AS/NZS 3725(2007). Other moduli were selected based on *New South Wales Roads and Maritime Services (RMS) Supplement to Austroads Pavement Guide to Pavement Technology – Part 2(Austroads, 2015)* with due consideration to the fact that these layers are in service (e.g. post crack modulus for Lean Mix Concrete). Dynamic load distribution is considered in accordance with AS/NZS 3725(2007) and AS 5100.2(2017).

Resulting stress distributions are presented in Figure 5. Stress distribution up to 0.4 m below pavement surface level is excluded from these plots as AS/NZS 3725(2007) stipulates that wheel loads shall be assumed to directly bear on the pipe under such circumstances.

It is noteworthy that the stress distributions presented in this paper are for traffic loads only. In addition to traffic loads, the weight of soil above pipes should also be taken into account in pipe structural assessment. These soil loads vary with depth of pipe installation, which could vary significantly depending on the type of service.

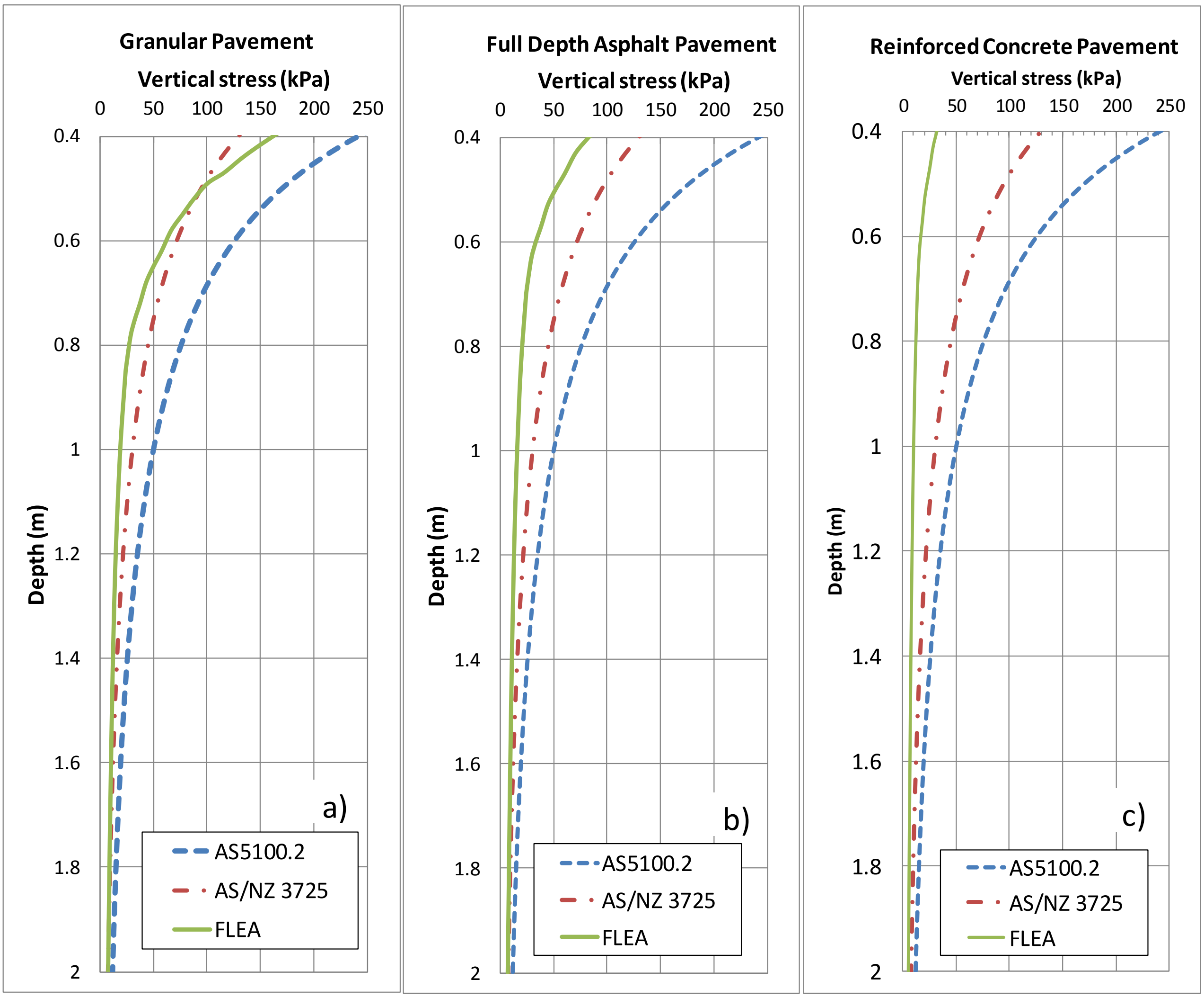


Figure 5: Comparison of stress distribution for W80 Loading for typical a) granular, b) full depth asphalt and c) reinforced concrete pavements

NOTE: Stress distributions within the first 0.4m are not presented as AS/NZS 3725(2007) stipulates that the wheel load is assumed to act directly on the pipe within this zone.

Based on Figure 5, the vertical stress outcomes generated considering stiffer pavement layers show significant stress reductions for all pavement types, as compared to the AS 3725(2007) and AS 5100.2(2017) approaches. The stress reduction increases with the stiffness of the pavement layers. Figure 6 presents comparison of traffic load induced stresses at three selected depths (i.e. 0.6 m, 0.8m and 1.0 m) to demonstrate the scale of reduction. Based on this figure, multi layered analysis yields stress reductions (at the selected depths) ranging from:

- 20% to 75% compared to the single layer method used in AS3725(2007)
- 40% to 85% compared to the single layer method used in AS5100.2 (2017)

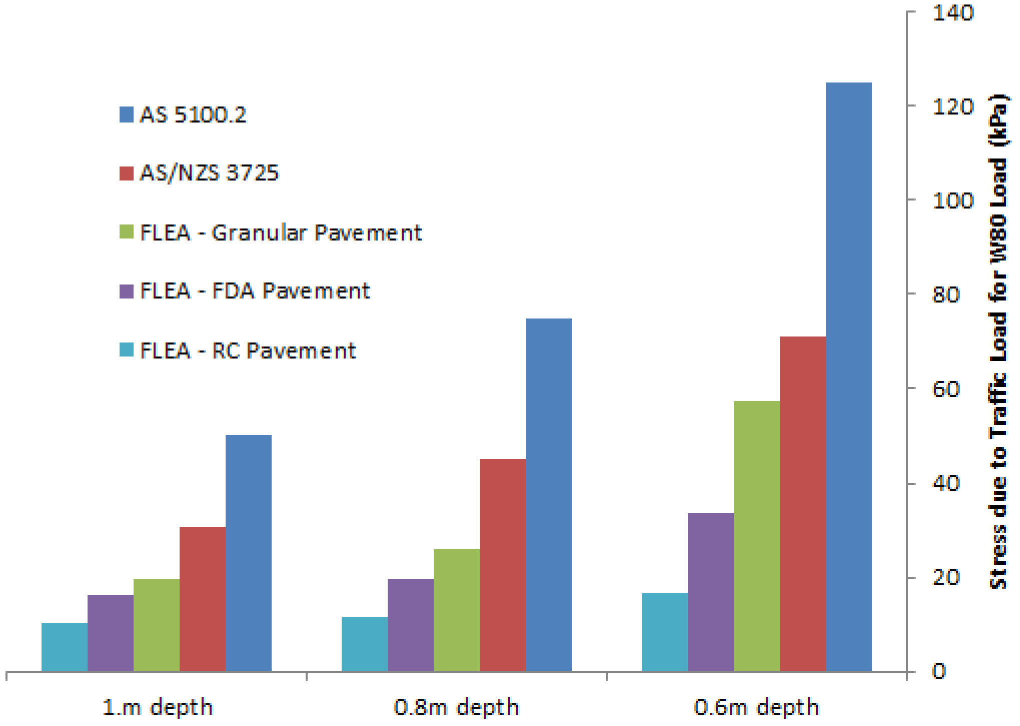


Figure 6: Comparison of traffic load induced vertical stress at selected depths for W80 Loading

5.2 M1600 MOVING LOAD

The M1600 Moving load model considers a series of axles together with a line load as depicted in Figure 7. The Stress distributions for the three pavement types in Tables 1a to 1c above were assessed. The M1600 load was modelled in two lanes with a lane factor of 0.8 for the second lane. The resulting stress distributions are presented in Figure 8.

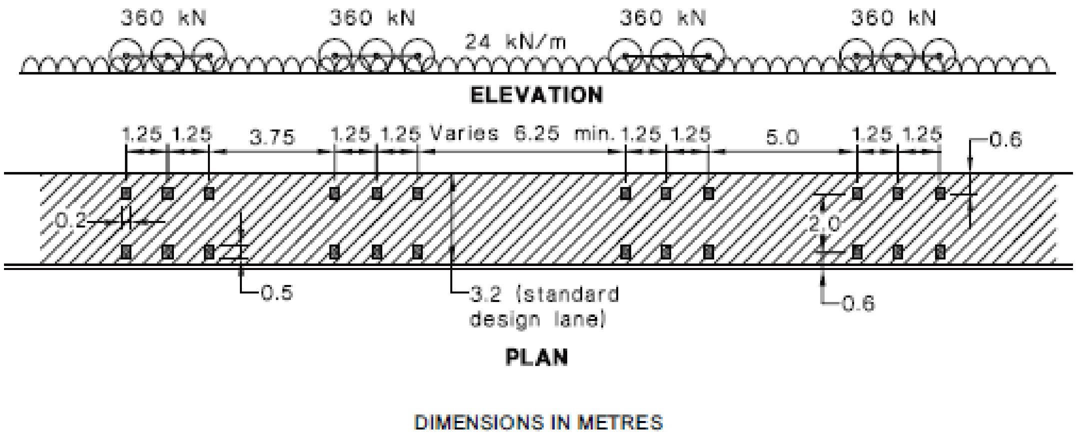


Figure 7: M 1600 Load layout from AS / NZS 3725(2007)

(AS 3725 Supp 1-2007 Figure C6. © Standards Australia Limited. Copied by AECOM Pty Ltd with the permission of Standards Australia under Licence 1707-c113)

Note: There are some differences between this figure and the latest version of AS 5100.2 (2017). It is assumed that latest version of AS5100.2 governs.

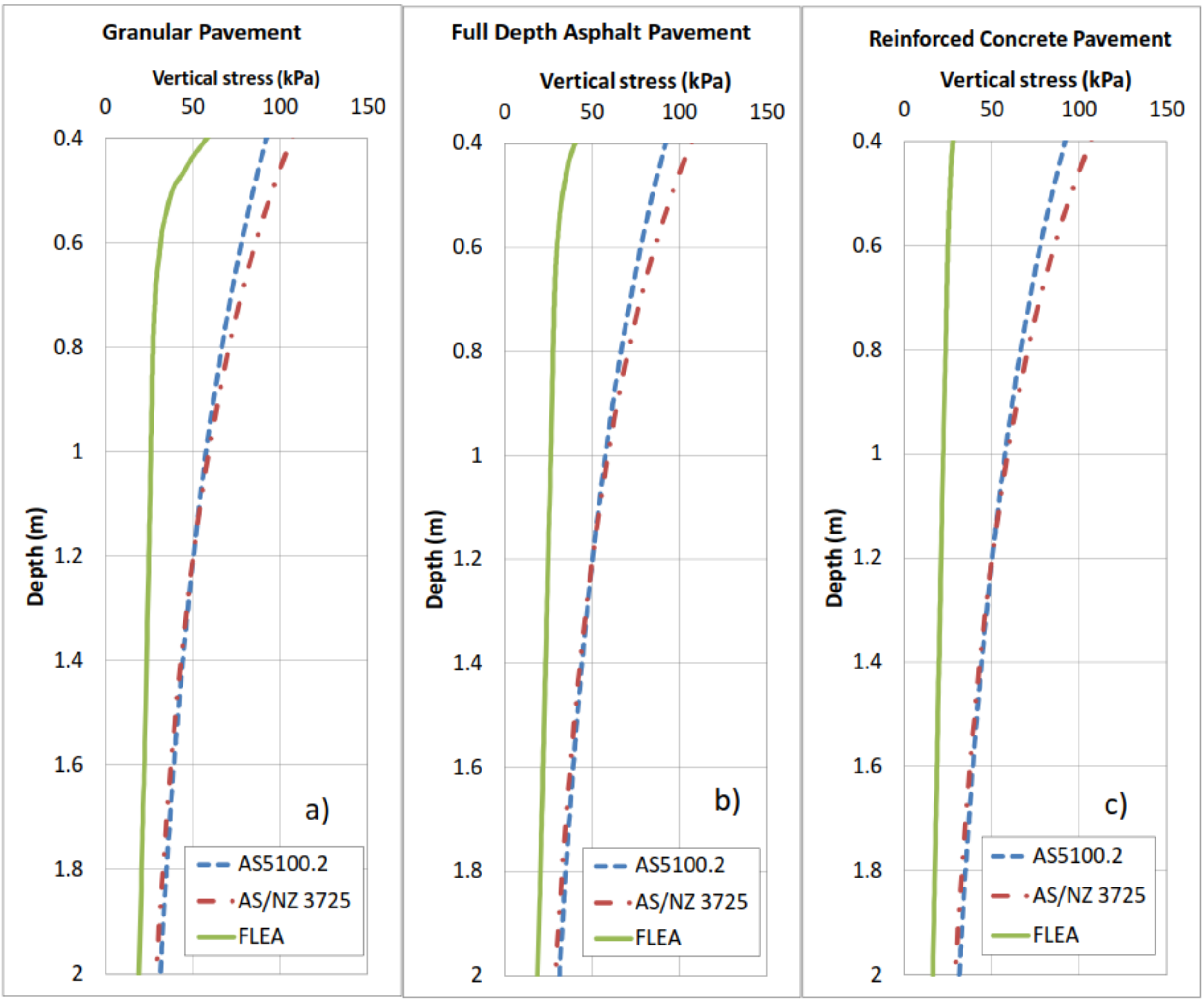


Figure 8: Comparison of stress distribution for M1600 Loading for typical a) granular, b) full depth asphalt and c) reinforced concrete pavements

Based on Figure 8, the vertical stress outcomes generated considering stiffer pavement layers show significant stress reductions for all pavement types, as compared to the AS 3725(2007) and AS 5100.2(2017) approaches. The stress reduction increases with the stiffness of the pavement layers.

Figure 9 presents comparison of traffic load induced stresses at three selected depths (i.e. 0.6 m, 0.8 m and 1.0 m) to demonstrate the scale of reduction. Based on this figure, multi layered analysis yields stress reductions ranging from 55% to 70% compared to the single layer methods used in AS3725(2007) and AS5100.2(2017).

Comparing Figure 5 and Figure 8 it is also inferred that single wheel loading is more onerous at shallow depths and M1600 loading governs as depths increase. This is consistent with commentary provided in AS/NZS 3725(2007). Comparing Figures 6 and 9, the percentage stress reduction is more pronounced for W80 single wheel loading as compared to M1600 loading.

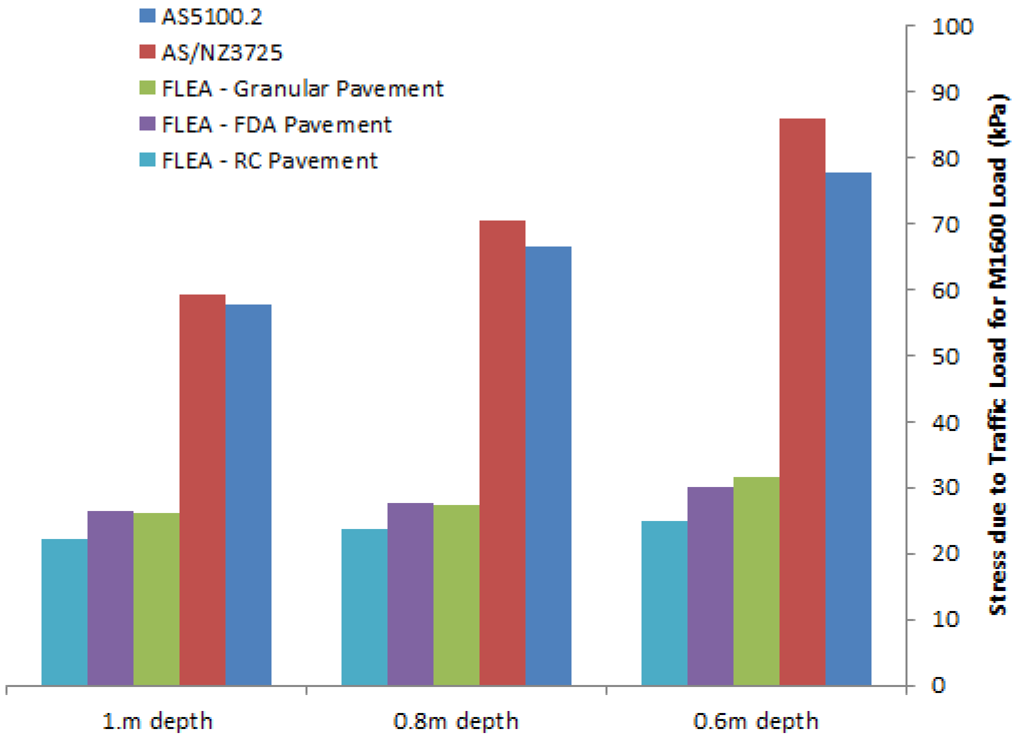


Figure 9: Comparison of traffic load induced vertical stress at selected depths for M1600 loading

5.3 LIGHT RAIL LOADING

With the number of light rail projects increasing in Australia, construction of light rail tracks over existing services is becoming more prevalent. The latest version of AS 5100.2(2017) recommends use of 0.5 times the 300LA “heavy rail” loading with nine axles for light rail loading assessment. Based on the AS 5100.2(2017) approach, a light rail load model as presented in Figure 10 was adopted for this paper. The track gauge is taken as 1.435 m.

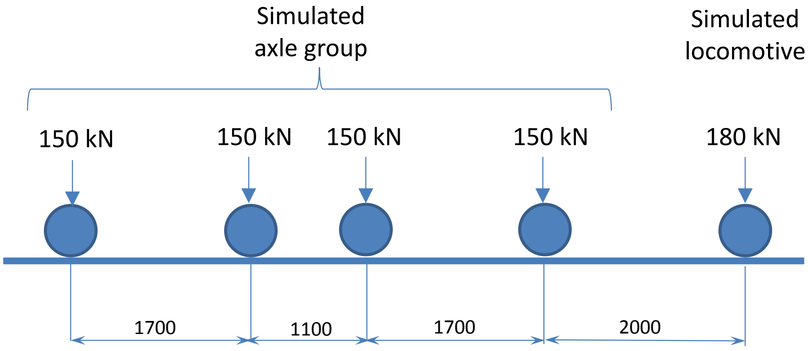


Figure 10: Light rail loading model based on AS 5100.2(2017)

The load distribution suggested in AS/NZS 3725(2007) for ballasted tracks is shown in Figure 11. This stress distribution is considered over a length of 1 m along the track alignment, but not exceeding the axle spacing. Similar guidance can be found in AS 5100.2(2017) for consideration of rail loads on bridges.

While it is unlikely to be the intention of the standard, this distribution is often used for fixed track configurations. For tracks fixed to a concrete slab, the stress impact at depth is much smaller. To demonstrate this, an approximate FLEA analysis was carried out, treating the slab as an elastic layer (refer to further discussions in Section 6.1) with layer configuration presented in Table 4.

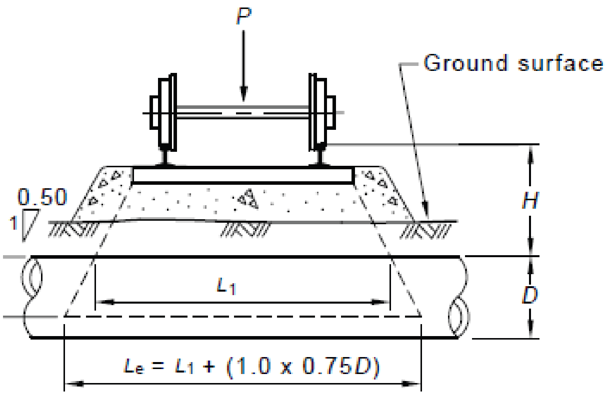


Figure 11: Rail Load Distribution for Ballasted Track

AS 3725-2007 Figure 10. © Standards Australia Limited. Copied by AECOM Pty Ltd with the permission of Standards Australia under Licence 1707-c113

Table 4: Light Rail Reinforced Concrete Track Slab

Layer No.	Material	Thickness (mm)	Young's Modulus (MPa)
Layer 1	Reinforced concrete	350	20,000
Layer 2	Lean mix concrete base course	150	700
Layer 3	Capping	200	100
Layer 4	Subgrade	Infinite	30

Figure 12 compares load distribution from the AS/ NZ 3725(2007) approach with FLEA analysis outputs for a single track configuration.

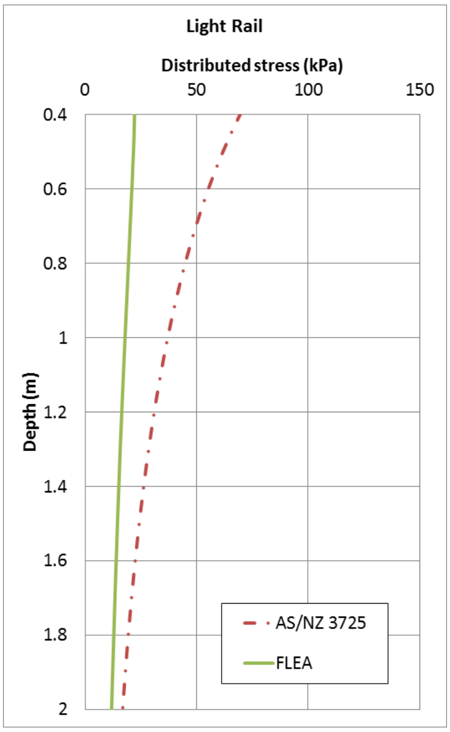


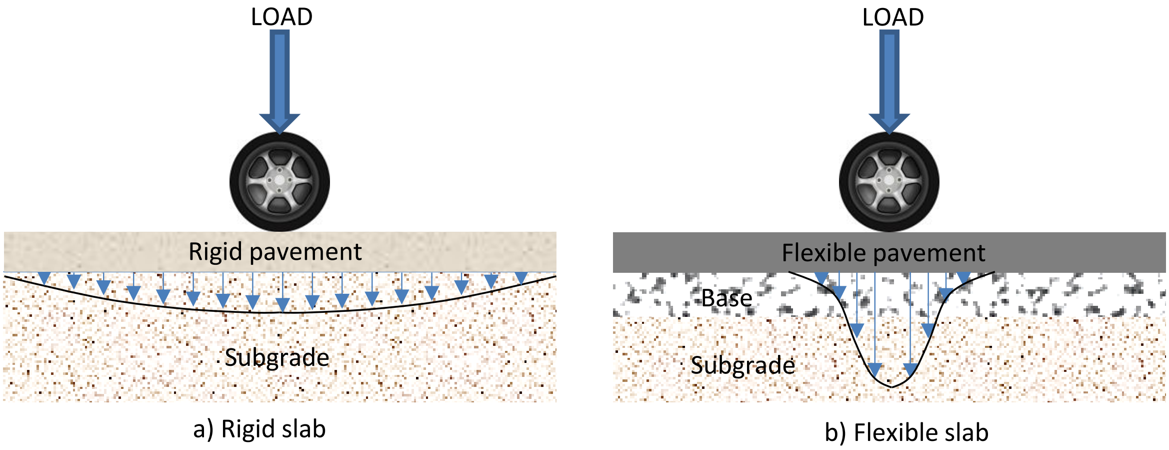
Figure 12: Comparison of AS/ NZ 3725(2007) rail load distribution with FLEA output

6 FURTHER CONSIDERATIONS IN OPTIMISING TRAFFIC LOAD ASSESSMENT

6.1 USE OF SLAB FLEXURAL RIGIDITY

Flexible pavements reduce stresses at subgrade layer via introducing a number of high stiffness layers between wheel contact area and top of subgrade. Subgrade stresses under rigid pavements are further reduced, by engaging a larger area via flexural rigidity (i.e. “slab action”) of the slabs as depicted in Figure 13.

FLEA analyses adopt a “flexibility approach” (Small and Booker, 1986) where the relatively high stiffness of the pavement layers is taken into account but not the “slab action / soil structure interaction” when relatively rigid slabs are used. Therefore, for reinforced concrete pavements and light rail track slabs, further refinement in traffic induced stress assessments could be made, by considering flexural rigidity of the slab and carrying out soil-structure interaction analysis.



a) Rigid slab

b) Flexible slab

Figure 13: Stress distributions under a) rigid slab and b) flexible slab (after Muench 2006)

6.2 CONTRIBUTION OF ADJOINING PIPE SEGMENTS (THAT ARE NOT SUBJECTED TO LOADING) IN LOAD RESISTANCE

AS/NZS 3725(2007) defines an effective length, L_e, as shown in Figure 14 to account for the fact that pipe sections that are not subjected to loading also contribute in resisting applied load. Depending on the relative stiffness of the pipe and bedding layers, the effective length could be significantly greater than that shown in Figure 14. Problem specific “beam on elastic foundation” or full numerical analyses could be carried out to optimise the effective length that is engaged in resisting applied loads.

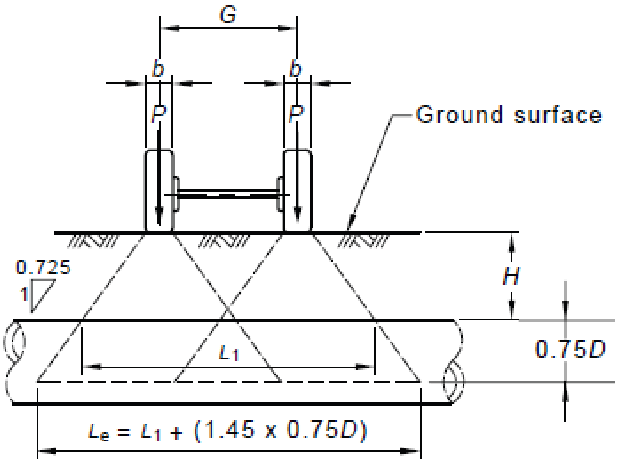


Figure 14: Effective length consideration in AS/NZS 3725(2007)

6.3 RELATIVE GEOMETRY BETWEEN PIPE AND WHEEL PATH

The AS/NZS 3725(2007) stress distribution approach considers the same stress at every point within the loaded area (see Figure 3) at a particular elevation. While stress distribution applicable at the worst case location is presented in Figures 5, 8 and 11, it would be possible to consider a spatial distribution of stress, if the wheel path or track centreline is not directly above the pipe crown. As illustrated in Figures 15 and 16, peak stresses are encountered below the wheel path (for single wheels) or centreline of tracks (light rail) and stresses reduce with lateral distance; moving away from the centreline of the loaded area.

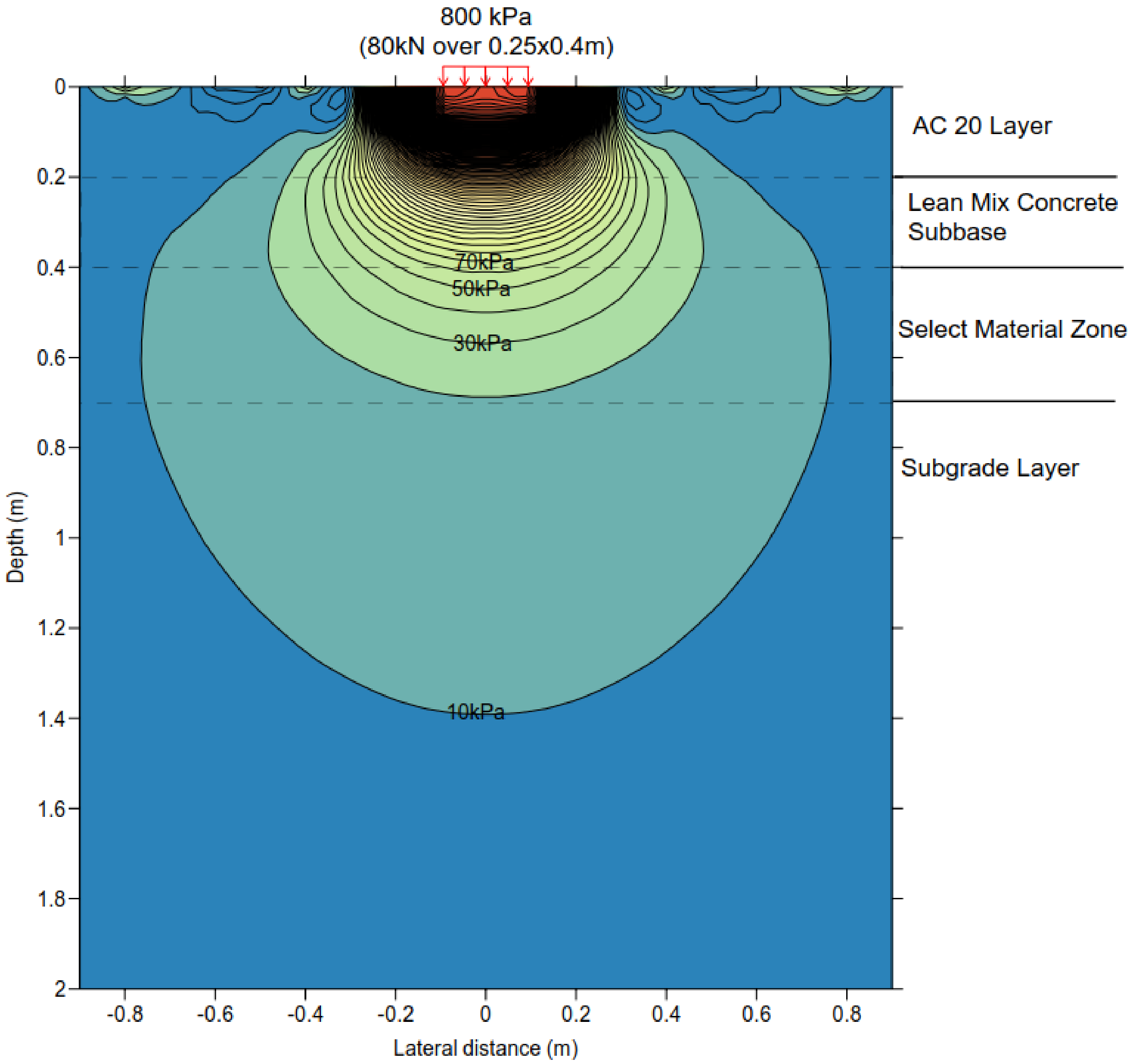


Figure 15**:** Typical FLEA 2-D stress distribution for W80 Loading for Full Depth Asphalt Pavement

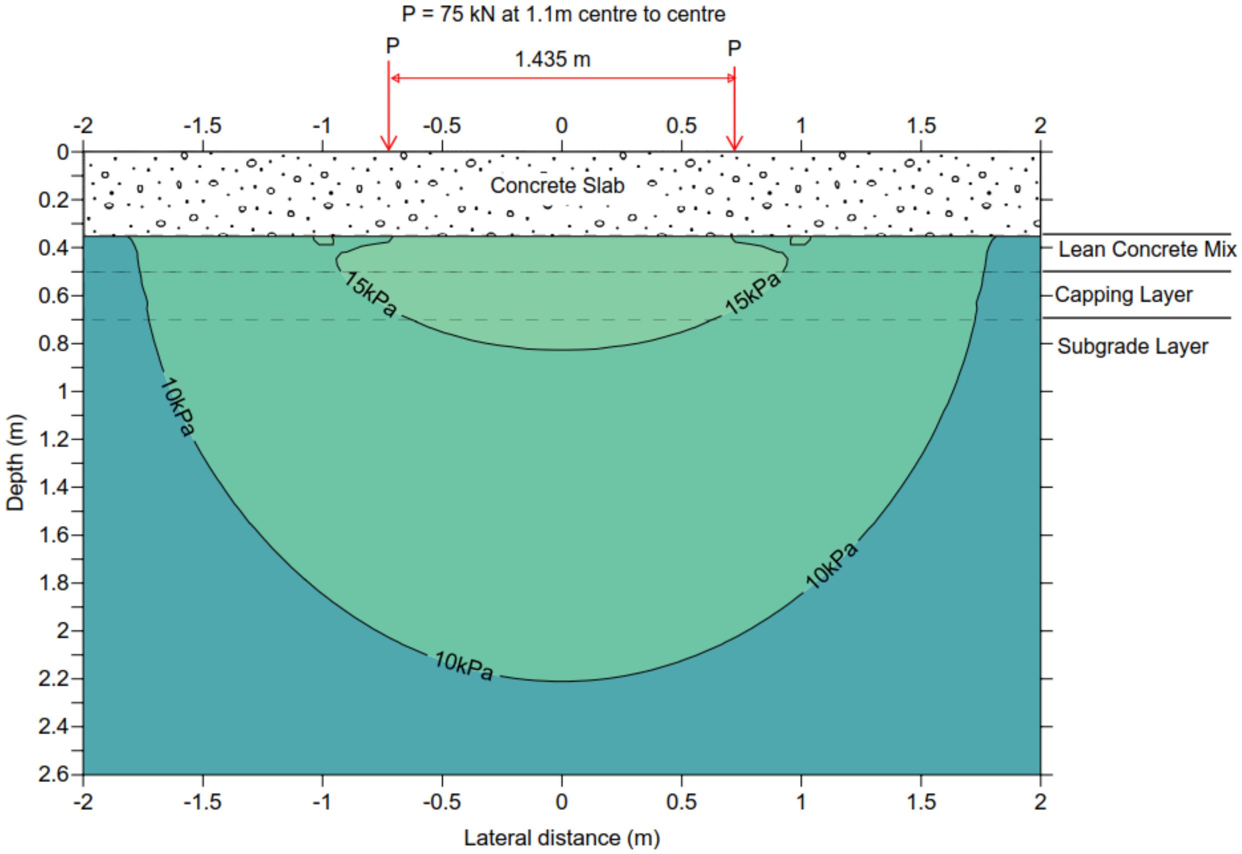


Figure 16: Typical FLEA 2-D stress distribution for light rail loading

7 CONCLUSIONS

Objective assessment of traffic load impact on pipes requires an appreciation of fundamentals from a number of disciplines. Depending on circumstances, this may involve:

- internal pressure and flow gradient requirements from a hydraulic perspective
- strength, deflection and fatigue requirements from structural perspective and
- stress influence and settlement considerations from a geotechnical perspective.

Guidance provided in Standards such as AS/NZS 3725(2007) and AS 5100.2(2017) on load distribution is primarily applicable to uniform layers of fill and natural subgrades of relatively low stiffness.

Flexible pavements reduce stress at subgrade layers via introducing a number of relatively high stiffness layers between the wheel contact area and the top of subgrade. This pavement response to traffic loading can be used when considering stresses on pipes overlain by relatively stiff pavement layers.

The standards do not restrict the use of problem specific analyses from first principles. Therefore, it is open to engineering practitioners to use solutions that are tailored to their particular circumstances. In this paper, the results of multi-layered analyses demonstrate that predicted vertical stress reductions ranging from 20% to 85% can be gained by considering the stiffness of typical pavement profiles overlying pipes. Such reductions in predicted stress may make a significant difference in the assessment of whether to retain or replace pipes impacted by new or upgraded infrastructure. Therefore, the use of multi-layer stress analyses could provide significant opportunities to reduce impact on schedule and cost.

8 REFERENCES

American Society of Civil Engineers and the Water Environment Federation. *Design and Construction of Urban Stormwater Management Systems*, ASCE Manuals and Reports of Engineering Practice No.77, 1992, WEF Manual of Practice FD-20, USA

Austroads. *RMS Austroads Supplement for Guide to Pavement Technology – Part 2: Pavement Structural Design*, Roads and Maritime Services, Sydney, Australia, 2015

Burmister, D.M. *The General Theory of Stresses and Displacements in Layered Soil Systems*, Journal of Applied Physics, 1945, **16**, pp.84-94, 126-127, 296-302

Burmister, D.M. *Evaluation of Pavement Systems of the WASHO Road Test by Layered Systems Method*, Bulletin 177, 1958, pp.26-54; Highway Research Board

Huang, Y.H. *Pavement analysis and design*, Pearson Prentice Hall, 1993, 2nd Edition

Muench, S. *Flexible Pavements*, Lecture Notes, 2006, *http://courses.washington.edu/cee320ag/Lecture/Pavement_Design.ppt*, accessed on 26/07/2017

Poulos, H.G., and Davis, E.H. *Elastic Solutions for Soil and Rock Mechanics*, Centre for Geotechnical Research, University of Sydney, Australia, 1974

Standards Australia. *Vitrified Clay Pipes and Fittings with Flexible Joints – Sewer Quality*, AS 1741:1991, Homebush, Australia, 1991

Standards Australia. *Precast Concrete Pipes (Pressure and Non-Pressure)*, AS 4058:1992, Homebush, Australia, 1992

Standards Australia. *Loads on Buried Vitrified Clay Pipes*, AS 4060:1992, Homebush, Australia, 1992

Standards Australia. *Bridge Design Part 2: Design loads*, AS5100.2:2017, www.saiglobal.com, 2017

Standards Australia. And Standards New Zealand. *Buried Flexible Pipelines Part 1 – Structural Design*, AS/NZS 2566.1:1998, Homebush, Australia, 1998

Standards Australia and Standards New Zealand. *Design for Installation of Buried Concrete Piles*, AS/NZS 3725:2007, www.saiglobal.com, 2007

Standards Australia and Standards New Zealands. *Design for Installation of Buried Concrete Piles – Commentary* (Supplement to AS/NZS 3725:2007), AS/NZS 3725 Supplement 1:2007, www.saiglobal.com, 2007

Small, J.C. and Booker, J.R. *Finite Layer Analysis of Layered Elastic Materials Using Flexibility Approach. Part 2—Circular and Rectangular Loadings*., International Journal for Numerical Methods in Engineering, 1986, **23**(5), pp.959-978.

Wardle, L.J., and Fraser, R.A. *Methods for Raft Foundation Design Including Soil Structure Interaction*, Symposium on Raft Foundations, 1975, Perth, Australia, November 1975