INVESTIGATION INTO SOME DESIGN ASPECTS OF BALLASTED RAILWAY TRACK SUBSTRUCTURE

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SUMMARY
Due to the daily congestion of highways, railways have become the most popular means of public transportation, which increased the demand for heavier and faster trains while keeping the cost of track maintenance at its minimum level. This requires an investigation into the effect of various design factors on the overall track performance. Such an investigation is very important for railway geotechnical engineers to arrive at optimum track design and maintenance.

Ballasted railway track substructure consists of graded layers of granular media of ballast and sub-ballast (capping) placed above compacted subgrade. Conventional methods for design of ballasted railway track substructure are based on simple theoretical or empirical solutions that assume a homogeneous half-space for all track layers and neglect the individual properties of each layer. This results in overestimation of the vertical pressure distribution with depth, leading to incorrect estimation of track thickness (i.e. ballast and sub-ballast). In addition, most available methods assume linear elastic behaviour for substructure materials.

In order to conduct more realistic multilayer simulations including material elastoplasticity, the more complex numerical solutions using the finite element method can be used. In this paper, two-dimensional versus three-dimensional finite element analyses using PLAXIS are carried out to investigate the validity of the simpler two-dimensional solutions. Furthermore, an elastoplastic constitutive model that represents more actual characteristics of track substructure materials is used and compared with the simpler elastic model. Detailed modelling of the track components including rail, sleepers, ballast, sub-ballast and subgrade is presented and the results are discussed.

INTRODUCTION
Conventional ballasted railway tracks combine a number of components including rail, sleepers, ballast, sub-ballast and subgrade. Ballast supports the imposed wheel load and transmits this load to the subgrade. Sub-ballast provides the effective drainage and filtration needed to protect the subgrade soil from softening and mud pumping.

The design of ballasted railway track foundations requires an accurate estimation of the granular layer thickness (i.e. the combined thickness of ballast and sub-ballast) that provides protection against subgrade failure induced by train loads. The design should also account for the deterioration of ballast and sub-ballast layers due to traffic loading so that the total deformation of track substructure should not exceed an acceptable value.

The basis for track substructure design used by most available methods is to calculate the minimum granular thickness that allows the transmission of imposed train loads at a tolerable pressure on top of the subgrade layer. This means that a reliable estimation of subgrade stresses caused by train loads is the key element in the calculation of the granular layer thickness.

Several simplified theoretical and empirical methods have been proposed in the literature to calculate the granular layer thickness. Among these methods are the method proposed by the American Railway Association [1], the British Railway Research method [2] and the Japanese National Railway Equations [3]. However, these methods assume a homogeneous half-space for all track layers and do not consider the individual properties of each layer. Several multilayer track models have also been developed for analysis of stresses in the track and subgrade. Examples of these methods include ILLITRACK [4], GEOTRACK [5] and KENTRACK [6]. However, these methods are based on an assumption of elastic behaviour of substructure materials.

In this paper, the more complex numerical solutions using the finite element method (FEM) is used so that a multi-layer track substructure and elastoplasticity can be incorporated in the design
of railway track substructure. The paper aims to investigate whether or not the simpler two-dimensional analysis is sufficient for design and can be used as an acceptable alternative to the more complex true three-dimensional simulation. The paper also investigates the applicability of using the elastic behaviour for track substructure materials compared with the more actual elastoplastic simulation.

DESCRIPTION OF FINITE ELEMENT TRACK MODELS

In this study, 2D and 3D railway track sections are numerically modelled using the finite element method. Detailed description of the developed finite element models and comparison of results are given below.

1. 2D Finite Element Model

The 2D finite element analysis is carried out using available commercial software package PLAXIS 2D Version 8.6 [7]. As shown in Figure 1, the 2D railway track section is discretized by utilising 15 node plane strain triangular elements for all parts of the track section. The plane strain simulation implies that the sleeper spacing has a negligible influence on the track performance. Due to symmetry, only one half of the track is considered in the numerical model. Roller boundary conditions are used in the vertical direction to warrant symmetry and to simulate end of soil, whereas fixed boundary conditions are used at the bottom to simulate bedrock.

All track parts (i.e. rail, sleeper, ballast, sub-ballast and subgrade) are represented by linear elastic materials. The train load is modelled by applying static line load and the rail is represented by an equivalent square of the same cross-sectional area. For all the finite element modelling conducted in this study, the minimum required mesh discretization is determined by carrying out a sensitivity analysis on various mesh dimensions until an optimal mesh size is obtained.

The track dimensions and material properties of track components are given in Table 1, which also contains the track properties needed for the 3D simulation that will be described later. This track is selected to represent timber sleeper tracks of the New South Wales State Rail Authority, Australia. The train wheel load is 150 kN, representing an axle train load of 25 tons with dynamic impact of 20% of the axial wheel load. The gauge length of the track is 1.4 m.

2. 3D Finite Element Model

The 3D finite element analysis is conducted using PLAXIS 3D Foundation Version 2.1 [8]. Figure 2 shows the 3D configuration used in the finite element analysis. The finite element characteristics and material properties are kept the same as those used in the 2D simulation, unless otherwise stated. As can be seen in Figure 2, the 3D track section is simulated using five sleepers spaced by a distance of 0.6 m centre-to-centre. Therefore, the track has a length of 2.6 m. It should be noted that five sleepers are used in this study as a comparison study carried out by Shahu et al. [9] for mesh discretization using five and seven sleepers indicated that the stresses and displacements beneath the rail seat can be sufficiently simulated using five sleepers. The track substructure is discretized using 15 node wedge elements. The rail and sleepers are simulated using 3D beam and floor elements, respectively. The train load is modelled by applying a concentrated load of 150 kN at the centre sleeper, as shown in Figure 2. The 3D track dimensions and material properties are given in Table 1.

3. Comparison between 2D and 3D Models

Figures 3 and 4 show the distribution of vertical displacement and vertical stress, respectively, underneath the rail seat for the 2D and 3D finite element models. It can be seen that the 2D model gives less settlement and stress along the track depth than those of the 3D model. This is because the 2D model neglects the actual horizontal extension of the individual layers, leading to a better stress distribution with depth and thus underprediction of the vertical displacement and induced vertical stresses caused by train loading.

As mentioned previously, the basis for design of track foundations is to allow the transmission of train loading in such a way that track substructure is protected against subgrade bearing capacity failure (the vertical stress on top of the subgrade layer should not exceed a tolerable value) and excessive track deformation (the total track deformation settlement should not exceed an acceptable value). This requires the calculations of the maximum vertical settlement on top of the ballast layer and the maximum vertical stress on top of the subgrade layer. Table 2 shows the results of the 2D and 3D finite element models in relation to the maximum design vertical displacement and stress.
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Figure 1: Finite element configuration used in PLAXIS 2D simulation

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Rail</th>
<th>Sleeper</th>
<th>Ballast</th>
<th>Subballast</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity, $E$ (MPa)</td>
<td>210000</td>
<td>10000</td>
<td>150</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>Poisson’s ratio, $v$</td>
<td>0.15</td>
<td>0.15</td>
<td>0.35</td>
<td>0.35</td>
<td>0.4</td>
</tr>
<tr>
<td>Unit weight, $\gamma$ (kN/m$^3$)</td>
<td>78</td>
<td>8</td>
<td>16</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>Inertia (m$^4$)</td>
<td>4.2E-5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cross-sectional area (m$^2$)</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>N/A</td>
<td>0.6*</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>0.15</td>
<td>0.2</td>
<td>0.35</td>
<td>0.15</td>
<td>3.0</td>
</tr>
<tr>
<td>Width (m)</td>
<td>0.15</td>
<td>0.25*</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Length (m)</td>
<td>2.6*</td>
<td>2.6</td>
<td>2.6*</td>
<td>2.6*</td>
<td>2.6*</td>
</tr>
</tbody>
</table>

*Parameters used for the 3D simulation only.

Table 1: Track properties used for the elastic 2D and 3D finite element analyses

Figure 2: Finite element configuration used in PLAXIS 3D simulation
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4. Effects of Elastoplasticity

The elastic modelling can be used to estimate the behaviour of materials prior to failure, but it is incapable of predicting materials behaviour for stresses that exceed the yield limit. Use of linear elastic analyses to represent soil behaviour is inappropriate and can lead to misleading results [10].

In this study, the effect of elastoplasticity in the design of railway tracks is investigated in terms of stress and deformation. An elastoplastic (Mohr-Coulomb) 3D model is performed using the mesh shown in Figure 2 and compared with the 3D elastic model developed previously. In both analyses, the elastic parameters used are identical, and the plastic properties for the elastoplastic analysis are given in Table 3. The deformed mesh and settlement contours obtained from the elastoplastic model are shown in Figures 5 and 6, respectively, and the comparison results between the elastic and elastoplastic models are depicted in Figures 7 and 8.

<table>
<thead>
<tr>
<th>Track component</th>
<th>Plastic property</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cohesion, c (kPa)</td>
</tr>
<tr>
<td>Ballast</td>
<td>0.0</td>
</tr>
<tr>
<td>Subballast</td>
<td>0.0</td>
</tr>
<tr>
<td>Subgrade</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3: Plastic properties used for the elastoplastic simulation

It can be clearly seen from Figures 7 and 8 that there are differences in the predictions from the elastic and elastoplastic analyses, with the elastoplastic analysis predicting higher vertical displacement and stress along track depth. The reason for this is that the elastoplastic analysis allows plastic deformation to develop and plastic failure to occur. This is demonstrated in Figure 9 by the failure mechanism developed underneath the rail seat of the central sleeper and is represented by the Mohr-Coulomb plastic points.

The track behaviour shown in Figures 7 and 8 is in agreement with the results obtained by Profillidis [11], who compared measured values of real track behaviour with elastic and elastoplastic finite element models and found that the elastoplastic model matches closely the measured values.
Figure 5: Deformed mesh of the 3D elstoplastic model

Figure 6: Settlement contours of the 3D elstoplastic model
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Figure 7: Vertical displacement of the elastic and elastoplastic models

Figure 8: Vertical stresses of the elastic and elastoplastic models

Figure 9: Mohr-Coulomb plastic points and failure mechanism
CONCLUSION

It is shown in this paper how the numerical modelling using the finite element analysis can be used to simulate the behaviour of ballasted railway track foundations. It was demonstrated that a reliable design of railway track foundations requires true 3D rather than 2D simulation. It was also illustrated that the use of elastic models for track substructure leads to inappropriate estimation of track deformation and stresses.

REFERENCES