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Back Analysis to Estimate Resilient Modulus of Soft Clay

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ABSTRACT: Selection of an appropriate resilient modulus for soft clay subgrade is important in the assessment of formation (sub-ballast) thickness and dynamic deflection of rail tracks. When no site specific laboratory cyclic triaxial tests or field measurements are available, published data can be used for the selection of resilient modulus. Sometimes, adopting a resilient modulus from the published data leads to a conservative design, leading to an increase in formation thickness and construction cost. This paper presents a back analysis carried out to estimate the resilient modulus of soft clay based on field measurements for a rail project at Hexham, New South Wales, Australia. The back analysis results indicated that a resilient modulus of 600 to 700 times the undrained shear strength of soft clay can be adopted for the design.

1 INTRODUCTION

1.1 Project Background

Hexham Relief Roads project (HRR), commissioned by the Australian Rail Track Corporation (ARTC), involved construction of five Relief Roads (tracks), a down coal track and associated infrastructures at Hexham in the NSW Hunter Valley, approximately 160 km north of Sydney. The alignment of the HRR was located over the low lying floodplain of the Hexham Swamp that comprised Quaternary Aged sediments (soft clay) overlying the Permian aged Tomago Coal Measures. Soft clay thickness varied between 12 m and 25 m within the project corridor. The length of each rail track varies up to 3.2 km.

1.2 Design Criteria

The formation design for the HRR project was carried out adopting two design criteria summarized below for a rail track configuration shown in Fig. 1.

Strength Criterion:
The formation thickness should be sufficient enough to reduce the risk of subgrade failure due to static and repeated train loadings.

Operational Criterion:
Dynamic deflection of the tracks should be less than the allowable limits (allowable limits for turnouts and plain tracks were 10 mm and 17 mm, respectively for the HRR project). In this step, dynamic deflection was predicted adopting the formation thickness assessed from Strength Criterion above to check whether it is within the allowable limit. If not, formation thickness was increased until the deflections are within the limit.

Any small increase in formation thickness will increase construction cost significantly considering the amount of material required to construct formation for six rail tracks over a length of 3.2 km. Therefore, formation design should consider appropriate resilient modulus for soft subgrade to develop an economical design. This paper summarizes a back analysis conducted to assess the resilient modulus of soft clay from field measurements.

2 RESILIENT MODULUS OF SOFT CLAY

Assuming specific laboratory cyclic triaxial tests were not carried out on the soft clay during the site investigation for the HRR project, published data was used for the estimation of resilient modulus for the initial design purposes. From a wide range of resilient modulus values available from published data, a resilient modulus of 500 times the undrained shear strength of the soft clay was adopted for
the initial design (Sukumaran, et.al. 2002, Abdul- 
Formation thickness was initially assessed 
adopting the strength criterion and then it was used 
to assess dynamic deflection of the tracks. The as-
sessed dynamic deflections exceeded the allowable 
limits, leading to an increase in formation thick-
ness and construction cost. Recognizing the fact 
that the adopted resilient modulus of 500 times the 
undrained shear strength for soft clay is relatively 
low, the HRR project team decided to measure dy-
namic deflection of an operating rail track located 
closer to the project corridor for the purpose of 
back calculating the resilient modulus. Adopted 
methodology to measure dynamic deflection and 
back analysis approach to assess the resilient mod-
ulus are summarized in the following sections.

3 PILE DRIVING MONITOR SURVEY

Pile Driving Monitor (PDM) survey technique was 
used to record the dynamic deflection of an operat-
ing rail track located close to the HRR project cor-
ridor. Originally developed for pile driving proce-
dures, the PDM can also be used to measure the 
deflection of rail roads, bridges and highways un-
der repetitive wheel loadings.

A PDM was set up outside the rail corridor in a 
stable platform. A target was then set up on the 
sleeper where deflection is to be measured. Initial-
ly, a baseline reading was taken to assess the sta-

tbility of the PDM and it indicated that the PDM 
settled by 0.4mm to 0.8mm when there is no trains 
on tracks. Then the dynamic deflection was re-
corded when train was passing. Recorded maximum 
dynamic deflection of the track was approximately 
6.5 mm when a train was passing (Fig. 2). There-
fore, the total dynamic deflection as assessed using 
the PDM readings can be in the range of 6.9mm to 
7.3mm.

4 GEOTECHNICAL MODEL

A geotechnical model was developed for the anal-
ysis based on the available cone penetration test 
and test pit results near the measurement location. 
The adopted material parameters and resilient 
modulus for each material is summarized in Table 1.

Table 1. Adopted Geotechnical Model

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (m)</th>
<th>Undrained Shear Strength(kPa)</th>
<th>Resilient Modulus,(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast</td>
<td>0.7</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Fill</td>
<td>0.3</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Stiff Clay</td>
<td>0.6</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Firm Clay</td>
<td>0.3</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Very Stiff</td>
<td>1</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Soft Clay</td>
<td>0.7</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Stiff Clay</td>
<td>0.5</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Soft Clay</td>
<td>1</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1.5</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Soft to Firm Clay</td>
<td>20</td>
<td>Increases from 16 at a rate of 1.2 kPa/m</td>
<td></td>
</tr>
</tbody>
</table>

5 TRAIN LOADINGS

The PDM readings were recorded when a train 
with four 30Tonne axles (refer Fig. 3) was passing 
measurement point at a speed of 15 km/h. A dy-
namic load allowance factor ($F_d$) was assessed 
based on the relationship reported by Li and Selig 
(1998) to predict the dynamic loads (Eq. 1).

$$F_d = \left[1 + 0.0052 \frac{V}{D_w}\right]$$ (1)

Where, $V$ (km/h) is the train speed and $D_w$ (m) is 
the diameter of wheel. The wheel diameter was as-
sumed to be 0.95 m.

Fig.3 Axle Configuration Considered for the Study (As per AS5100.2 – 2004, excluding simulated locomotive)
6 BACK ANALYSIS METHODOLOGY

Ballast and formation fill will distribute train loads in both longitudinal and transverse directions to the alignment of the rail track. Commercially available computer software, Plaxis3D, was used in the back analysis to model the load distribution. The PLAXIS 3D finite element modeling has been carried out simulating the axle loads shown in Fig. 3. Adopted sleeper/rail configuration is presented in Fig. 4.

Fig. 4 PLAXIS 3D Modeling Geometry

Considering the symmetric nature of the model geometry shown in Fig. 4, a quarter of the model geometry has been adopted in PLAXIS 3D modeling (refer Fig. 5 below). Symmetric modeling adopting a quarter of the model geometry will capture the effect of loading from four design axles. The load applied on the rail is 162kN at each axle location, which is the half of the design axle load of 300 kN multiplied by a dynamic load allowance factor of 1.08.

In general, the following construction stages were considered for this study:

1. Initial condition – \( K_0 \) procedure
2. Apply repeated train loadings – Plastic analysis.

For all stages prior to applying repeated wheel loadings, formation fill, ballast and existing fill were modeled using a Mohr-Coulomb model while a Soft Soil model was adopted for the soft soil layers. When the repeated wheel loadings were applied, all materials were switched to drained linear elastic material with appropriate resilient modulus provided in Table 1. The Poisson’s ratio for the soft soil layers during the repeated train loadings stage was assumed to be 0.49 considering undrained conditions.

A beam element was adopted to model the 60 kg rail in PLAXIS 3D with the following sectional parameters (As per ARTC code of practice Section 1: Rail - 2011 and AS1085.1-2002):

1. Cross sectional area = 7,725 mm\(^2\)
2. Second moment of area = 29.3x10\(^7\)mm\(^4\) about horizontal axis of rail cross section
3. Second moment of area = 4.9 x106mm\(^4\)about vertical axis of rail cross section

An elastic modulus of 200 GPa was adopted for the rail. Resilient modulus of soft clay has been increased until the dynamic deflection assessed from PLAXIS 3D modelling matched with the PDM measurement. Resilient modulus of ballast and existing fill were not adjusted for the back analysis purposes.

7 RESULTS

The measured dynamic deflection using PDM technology at the selected location was in the range of 6.9mm to 7.3mm for a train with 30 T axles. Adopting resilient moduli of 600 and 700 times of the undrained shear strength for soft clay resulted in a dynamic deflection of 7.2mm and 6.5mm, respectively. These findings from this case study have been used to optimize the formation thickness for the HRR project.
8 CONCLUSIONS

Resilient modulus of soft clay is important parameter in the assessment of formation thickness and dynamic deflection of train tracks constructed over soft clay subgrade. Resilient modulus assessed from published data led to increased formation thickness and construction cost in the HRR project. Back-analysis of field dynamic deflection measurements demonstrated that the resilient modulus of 600 to 700 times the undrained shear strength can be adopted for the soft clay present in Hexham Swamp area. The findings from this case study have been applied to optimize the formation thickness and thereby to reduce the construction cost of the HRR project. The HRR project has been successfully completed in 2014 and opened to traffic.

REFERENCES


ARTC Code of Practice (2011). Engineering (Track & Civil), Section 1: Rail.


