CASE STUDIES IN RAILWAY CONSTRUCTION

TRANSITION ZONES

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An abrupt change in the vertical stiffness of the track causes the wheel to experience an equally abrupt change in elevation because of the uneven track deflection. The change in elevation causes vertical acceleration of the vehicle mass that generates an increase in the applied loading. This mechanism can be self-perpetuating as the dynamic loads increase the differential deflections and settlement leading to even higher forces (Kerr and Moroney 1993; Frohling et al. 1995; Hunt and Winkler 1997).
The effect of the load increase depends on the direction of the train. When the train is moving from a higher to a lower stiffness condition—such as exiting a bridge deck, grade crossing, or tunnel invert—the dynamic load is applied to the lower-stiffness track, increasing the rate of settlement. This condition is characterized by deterioration of the track geometry, ballast migration, and tie movement on the lower-stiffness track.
When the train is moving from a lower- to higher-stiffness track, the load increase occurs on the high-stiffness side of the transition over a short distance and is more of an impact loading. In this situation, typical problems are rail surface fatigue, tie deterioration, and rail seat pad deterioration. In addition to the track stiffness change, the damage potential at track transitions is related to vehicle axle loads, speeds, and suspension characteristics.
Typical differential settlement of a freight railroad ballasted track bridge approach
Cracked concrete ties at the abutment of a freight railroad ballast deck bridge caused by impact loads
Even if the dynamic effects are minimal, at-grade ballasted track may inherently settle more than ballasted track on a structure or direct fixation track, creating a dip in the surface at the transition. This is especially true when the structure abutment is built on a deep pile foundation where settlement is negligible.
Settlement of at-grade track can be highly variable because of geotechnical issues affecting the subgrade performance such as low strength soils, deficient soil placement and compaction, poor drainage, and erosion (Briaud et al. 1997; Smekal 1997; Hoppe 2001). Environmental factors such as wet/dry and freeze/thaw cycles also affect subgrade settlement behaviour.
It is clear that the above issues are related and whether considered from the viewpoint of uneven track stiffness and deflections or differential settlement driven primarily by geotechnical conditions, the goal of any technique intended to improve the performance of transition track is to minimize dynamic loads by equalizing or smoothing the vertical support condition and the dissipation of dynamic energy across the transition.
Transition Remedies

• In the literature, a number of remedies have been proposed or used to provide gradual stiffness transition. The following is a summary and discussion of those remedies.
Kerr and Moroney (1993) propose the following three categories of track transition remedies:

• Smoothing the stiffness/modulus step change at the interface by gradually increasing stiffness on the lower-stiffness side of the transition.

• Increasing the bending of the rail-tie structure (track panel) on the low-stiffness side of the transition.

• Lowering the stiffness on the high side of the transition.
Transition remedy in which the stiffness step change is modified with a gradual increase in stiffness.

Note: $x$ = distance, $k$ = stiffness
Increasing Track Stiffness with Long Ties

• One of the oldest, simplest, and most widely used transition designs is installation of a series of increasingly longer ties on the ballasted track side of the transition.
• This method assumes the track stiffness is increased by the larger bearing area of the ties. However, as Kerr and Moroney (1993) point out, its effectiveness
• depends on uniform density of the ballast beneath the tie from the gage-side rail seat to the end of the tie (i.e., uniform tamping in this area). Longer ties may also exceed the embankment width on narrow bridge approaches, allowing ballast to migrate from the tie ends.
• To increase stiffness, they recommend longer ties at reduced spacing and/or increasing the tie cross section, which in effect creates a stiffer track panel.
Approach ties for open deck bridges and trestles
HMA Underlayment

• The positive performance of an HMA pavement layer placed between the subgrade and ballast to reinforce weak subgrades is well documented in Rose 1998, Rose et al. 2002, and Li et al. 2001. These studies indicate that when properly designed and installed an HMA layer will reduce subgrade stresses and differential settlement and extend track maintenance cycles.
• Because it is a structural layer, HMA can reduce subgrade stresses to levels that will not exceed the compressive strength of low-strength soils. However, in tests on the Union Pacific Railroad, Li and Davis (2005) found that HMA, placed on the approach to a ballast deck concrete bridge with a well-compacted subgrade, did not reduce the geometry deterioration of the approach compared with a similar approach without HMA.
• The HMA layer provided little improvement to a subgrade with high load-bearing capacity, and the differential settlement seen on the approaches was caused primarily by settlement in the ballast layer rather than the subgrade.
• These results suggest that HMA and other methods used to improve performance of weak subgrades, such as geocell and soil cement, will not improve ballast performance on stiff subgrades. For cases in which the approach track stiffness is already high, it would appear that trying to further increase the approach stiffness is not as effective as reducing the stiffness of the bridge track.
Additional Rails

- The German Federal Railways have developed a design for the InterCity Express (ICE) high-speed lines on which lengths of rails are installed between the running rails and on the field side of the running rails to stiffen the ballasted track panel (Kerr and Moroney 1993). This condition often exists by default, when guard rails installed on open deck bridges extend beyond the abutment to the ballasted track.
**Concrete Bridge Approach Slabs**

- A reinforced concrete slab that rests on the abutment or slab structure and is tapered toward the at grade end is often used at transitions to direct-fixation aerial structures and tunnel/subway inverts. AREMA recommends using a slab that is a minimum of 20 ft long and that is tapered from 18 in. at the structure end to 12 in. at the at-grade end.
• General specifications for an approach slab design, based on a successful trial in the United Kingdom, are provided by Sharpe et al. (2002). In addition to the slab, this design calls for vertical adjustment of the rail on the direct-fixation bridge deck. The adjustable fasteners permit the rail on the ballasted side to be raised higher than the desired final elevation and to settle to the desired final elevation (design tamping).
**Section 1:**

Detail of ballasted section superimposed on end section of embedded track 115 re rail flangeway flare.

**Section 2:**

Typical track & slab installation.

**Ballasted / Embedded Track Plan View:**

Ballasted track installation

Embedded track installation

% of first tie

% of track drainage trough

**Transition Between Ballasted Track and Embedded Track Installations:**

Tie spacing per 10 concrete ties spaced at 610 (24") centers

Top of slab

Top of rail

Ballast

Transverse drain pipe

Top of subgrade

Subballast base pad

Transition slab

610 (20") -
Slab Track Approach

- Concrete approach slabs 25 ft in length were installed at the Transportation Technology Center to provide the transition from at-grade, concrete-tie track to a 500-ft-long concrete slab track test section (Bilow and Li 2005). The cast-in-place, 12-in.-thick reinforced concrete approach slab, prior to construction of the slab track. This transition design uses concrete ties with about 16 in. of ballast between the ties and the approach slab. The slab also has vertical walls to confine the ballast shoulder below the subgrade level.
• Track modulus data taken on the completed track showed the modulus at the approach slabs to be more than two times the modulus of the slab itself. In this case, the stiffness of the slab track direct fastening system had been successfully designed to approximate the nominal modulus of the surrounding wood-tie track (approximately 2,500 lb/in./in.). But the approach slab transition was over designed, creating an unnecessarily high (6,000 to 7,000 lb/in./in.) track modulus at the interface.
Slab track transition
Piles

- In addition to stone columns, Li et al. (2003) indicate that other types of piles, including concrete, timber, and sand columns are accepted methods of stabilizing weak subgrades. Unless the end of the pile is on a firm foundation, skin friction provides most of the load transfer capacity. Therefore, the pile’s effectiveness will depend on its length, and different lengths can be used to smooth the stiffness of the approach.
Other Geotechnical Considerations

• The use of stone columns, HMA, soil cement, geosynthetic materials, and piles are all techniques that can be used to reduce differential settlement of an approach track by reinforcing or stabilizing a weak subgrade.
However, consideration should also be given to maximizing the subgrade performance, specially during construction, with established geotechnical best practices such as the following:

• Determining the soil characteristics prior to construction by performing in situ testing.

• Using select noncohesive soils or applying admixtures to existing soils if needed to improve subgrade strength.
• Maintaining optimum moisture content and using correct compaction techniques for the soil type being placed, as well as ensuring adequate compaction when placing soil next to structures such as abutment backwalls.

• Ensuring maximum and uniform soil density by performing adequate soil density testing during construction.

• Removing ruts, crowning or sloping the subgrade surface, and/or using edge drains at the toe of the ballast section to prevent pocketing of free water in the track granular layer.
• Lowering ground water levels or installing cutoff layers if needed to prevent capillary movement of ground water upward into cohesive soil embankments.
• Allowing for adequate embankment width to accommodate the ballast/subballast depth.
• Allowing for adequate embankment slope angles or the use of benches, retaining walls, or sheet piles for slope stability and control of erosion.
Hole boring in approach subgrade for stone column
Stone columns installed in approach subgrade
Reducing Track Stiffness on Ballast Deck Bridges

• Several test sites were established on a high density freight route to determine the effectiveness of various tie materials at reducing the track stiffness on ballast deck bridges (Sasaoka et al. 2005). In all cases, concrete ties were installed on the approach and on the ballast decks.
Two methods were tested to reduce the bridge track modulus:

1. replacing concrete ties with composite (plastic) ties on the bridge deck and

2. installing concrete ties on the bridge deck with 1-in.-thick rubber pads cast into the bottom of the ties.
Rubber Tie Mats

- Another technique to reduce the stiffness on a ballast bridge deck was developed in Japan in the 1970s for the Shinkansen high-speed network. According to Li et al. (2003), rubber mats were placed between the ties and ballast to reduce dynamic loads and ballast deterioration. The shape of the mats was designed to achieve a specific spring rate, and results of extensive testing indicated that the mats were effective in reducing ballast wear. There was no mention, however, of how well the mats attenuated the dynamic loads or the quality of their long-term performance.
Dynamic design of track transition between two different slab tracks

- Case study
With the development of high-speed rail system, various types of slab track were put into service in Europe, China and Japan.
• Generally speaking, it has been substantiated that the noise level on slab track was 5dB higher than that on the ballast track. (Quarterly report of RTRI, 1997)

• Rail vibration levels on the slab track are 5db higher that those on the ballasted track, particularly for frequencies above 1kHz. (Wang 2010)
• In order to reduce track vibration into surrounding structures, new slab track is specially designed for vibration sensitive areas like railway stations by inserting soft rubber mats under slabs. The newly designed track is referred to as floating slab track.
Fixed slab track
Floating slab track

- Slab
- Slab mat
- Slab base
• At the transition point between fixed slab track and floating slab track, a moving wheel experiences a rapid change in elevation and dynamic problems occur because of the abrupt change in the vertical track stiffness.

• Transition regions require frequent maintenance. When neglected, the track geometry will deteriorate at an accelerated rate. (Lei & Zhang, 2011)
The modelled structure
• Track stiffness \((K_t)\) is the ratio of the applied wheel load \((P)\) to rail deflection \((y)\):

\[
K_t = \frac{P}{y}
\]
• Track modulus is often used as a measure of vertical stiffness of the rail foundation and is defined as the supporting force per unit length of rail per unit vertical deflection under a vertical load, as determined by the following equation (Selig and Waters 1994):
\[ u = \frac{1}{4} \sqrt[3]{\frac{K_t^4}{EI}} \]
• The dynamic analysis results show that the wheel/rail interaction is larger when vehicle passes the transition from low-stiffness side to high-stiffness side, compared to the passing in the opposite direction.

• Even without any initial track irregularities, an abrupt track stiffness change alone would lead to 76% higher dynamic load than static load in the transition.
$F_d / F_0 = 120.6 / 68.6 \approx 1.76$

Dynamic amplification factor:

- Fixed slab track
- Floating slab track

Distance (m)

Wheel/rail force (kN)
• The rail deflection difference is 1.5mm occurring in about 2m.
• The maximum variation rate of rail deflection is 2.7mm/m, far more than expected.
• At the transition point between fixed slab track and floating slab track, a moving wheel experiences a rapid change in elevation and dynamic problems occur because of the abrupt change in the vertical track stiffness.
• Track stiffness/modulus: 3, 4 times
• Wheel/rail contact force: 68.6→120.6kN, 1.76
• Rail deflection: 1.5mm/2m, 2.7mm/m
Transition Remedies

Increase stiffness of low-stiffness side
• Additional rail
• Long/wide sleeper
• Reducing sleeper spacing
• Approach slab
• Glued ballast

And/or Decrease stiffness of high-stiffness side
• Rail seat pad
• Sleeper pad
• Slab mat
• Ballast mat
Transition Design

Transition length: $25m < L < 50m$, $6.54m \times 5 = 32.7m$ \(\checkmark\)
• Equalize the rail deflection
• Provide a gradual stiffness increase
<table>
<thead>
<tr>
<th>Railway track</th>
<th>Rail deflection(mm)</th>
<th>Slab mat stiffness(MN/m²)</th>
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</table>
A ‘gradual’ increase in track stiffness and modulus does not mean linear change.
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Research Results Digest 79
DESIGN OF TRACK TRANSITIONS
Washington, 2006
Tao Xin, Uday Kumar és Liang Gao: Dynamic design of track transition between two different slab tracks

http://www.railwaygroup.kth.se/polopoly_fs/1.347143!/Menu/general/column-content/attachment/Tao%20Xin%20et%20al.pdf