Designing Durable Track Support for Higher-Speed Trains Using Track Geotechnology

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ABSTRACT

Amtrak is frequently given the task of designing cost-effective new track construction over old roadbed at locations where increased capacity is required. Much of this construction is planned for operating speeds in excess of 100 MPH. There is a considerable challenge associated with building track to modern standards for higher speeds on roadbeds that were constructed in the 1800s. In addition, strict requirements are imposed on funding so that new right-of-way or wetland impacts are kept to the absolute minimum.

The geotechnical challenges include determining the adequacy of the existing roadbed material, assessing subgrade strength, designing the required ballast and subballast thicknesses, establishing proper drainage, and ensuring slope stability. The design has to consider the amount of traffic (freight and passenger), train speeds, track centers, right-of-way access, and the slope encroachment created by the new construction. The work is greatly aided by the use of ground penetrating radar (GPR) which provides a continuous measurement of depth to the subgrade along maintenance-of-way roads where the new tracks are to be built. GPR is also used to find locations of both soft soil, as indicated by a deformed subgrade surface profile due to past loading, and locations of water accumulation. Gradation analyses are used to determine if existing excess ballast or subballast could be blended with new ballast or subballast, thereby reducing disposal costs and the amount of new material required. Lastly, the required new granular layer thickness (ballast plus subballast) is determined by using track settlement models in combination with geotechnical data and GPR data to limit track settlement to an acceptable amount over the track life. Amtrak applies these tools and methods in an effort to design track with a low life-cycle cost by reducing “upfront” track construction costs and by minimizing the maintenance needed over the track life.

INTRODUCTION

Amtrak has employed some of the latest design methods and investigative tools to build cost-effective new track over old roadbeds to accommodate increased capacity and higher operating speeds. This paper will discuss these methods and tools and how the measured geotechnical information was used to assure the track design would provide durable service with a minimum of required maintenance during its life. Some of the challenges faced in the design were: 1) increasing the capacity of the railroad to accommodate more frequent passenger and freight trains which will be in part heavy haul, 2) increasing operating speeds to over 100 mph, 3) the need to build track to modern standards on roadbeds created in the 1800s, 4) the need to minimize impacts on rights-of-way, wetlands, and slopes, 5) strict requirements on funding, and 6) the careful selection of the proper methods and tools to obtain the necessary information for
design. Despite the considerable challenges that were encountered, Amtrak was able to design new track to meet these requirements using advanced design methods.

**Adapting New Track to Old Roadbeds**

Old roadbed brings pre-existing problems with drainage, slope stability and other geotechnical issues to the new track constructed over it. The difficulty of designing new track for construction on old roadbeds becomes apparent when considering that roadbed construction in the 1800s typically used only locally available materials for fill and roadbed placement, applied a minimal amount of compaction, used limited geotechnical information, may or may not have provided adequate drainage and a subballast layer to separate ballast from fine-grained subgrade, and used a “one-size-fits-all” approach to ballast layer thickness with little regard to the quality of local subgrade. Furthermore, the roadbed width tended to be minimal which limits its ability to accommodate a modern-day track design with full-width shoulder ballast and increased clearance requirements (center-to-center spacing) between tracks. Example track cross sections showing newly constructed Track 2 in a cut area (Figure 1a) and in a fill area (Figure 1b) indicate the restrictions due to either limited roadbed width or wetlands.

![Figure 1a. Cut area](image1a)

![Figure 1b. Fill area](image1b)

As an example of how old roadbeds could provide “built-in” problems to new track construction, consider Figure 2 which shows track constructed in the very early days of railroading (circa 1830) with a tongue and grooved iron strap fastened to a wooden rail. These wooden rails rested on stone blocks that were in turn supported by loose stone aggregate that was placed in the excavated soil. As the track structure continued to evolve, the ballast became
continuous, more distinct, and recognizable as a layer. However, the old standard practice often allowed significant overstressing and deformation of soft subgrade (ballast pockets) with subsequent retention of water in these pockets which often remain in the roadbed to this day. These problem locations must be identified and remediated so that modern track constructed over them does not continue to settle excessively. The next section describes measurements that are made to identify such locations where geotechnical and drainage concerns exist and determines the needed improvements before constructing new track.

Figure 2 Track construction circa 1830 (from Stevens, 1926)
Use of Ground Penetrating Radar Data for Track Substructure Design

One of the first decisions Amtrak made was to investigate the existing roadbed conditions using Ground Penetrating Radar (GPR) to produce quantitative information of substructure conditions. GPR has the ability to map key railroad track substructure (ballast, subballast and subgrade) conditions quickly on a continuous, top-of-rail, nondestructive basis. Analysis tools have been developed for interpreting GPR data that can provide a variety of parameters related to track condition including the thickness of subsurface layers, the relative amount of moisture present, and the relative degree of ballast fouling. Locations of geotechnical and drainage concerns can be identified and the source of the problem can be determined, especially when GPR is used in combination with other tools and data.

Figure 3a (courtesy of HyGround Engineering) shows the common arrangement of GPR antennae during measurement where they are attached to a hi-rail vehicle. Figure 3b shows an alternative arrangement used in these investigations, with the antennas being dragged behind the vehicle along the maintenance-of-way access road to measure the subsurface conditions of roadbed over which the track is to be built.

GPR system used to investigate maintenance-of-way access road for new track (right photo). When the GPR signals are transmitted downward and subsequently reflected back to the receivers, they encounter substructure layer boundaries such as ballast, subballast and subgrade. These signals can be processed to show depth to the subgrade and the variation of this depth along and across the track. In this way, the presence of a soft and deforming soil condition in need of remediation can become apparent from the resulting distorted and varying subgrade profile as shown in Figure 4.
Figure 4. Plan view of subgrade surface elevation for two track right-of-way, with individual track rails shown (upper). Cross-section of track showing subgrade surface deformation (lower).

**Track Geometry Data**

Track geometry car data from past measurements on the existing track was also used to determine locations that have a history of repeated profile and cross-level geometry errors that may be attributed to soft subgrades which are in need of remediation. Figure 5 shows how track geometry data complemented the GPR measurements. The top portion of Figure 5 maps the depth from top of tie to the subgrade, showing the darker colored area corresponding to the increased depth of a ballast pocket over a soft subgrade. This ballast pocket location and its extent along the track is also confirmed by the growing track geometry profile roughness over time at the same location shown in the lower portion of Figure 5.
Figure 5. Plan view of GPR-indicated ballast pocket (top) and corresponding progressing surface roughness from repeated geometry car measurements (bottom)

Therefore, these tools can provide locations and root causes of geotechnical concerns, especially if used in combination with other tools and data. In addition, these tools can be utilized to determine where new subsurface investigations may be needed.

**Lidar**

Amtrak used Lidar to determine surface drainage directions and drainage areas for design. Although useful in fill and at-grade sections, Lidar is of particular value for drainage investigations in cut areas as shown in the upper and lower portions along the track of Figure 6. The high resolution provides a detailed surface image showing local drainage features as well as evidence of slope movement.

Figure 6. Example LIDAR image showing cut and fill sections along the track
Subgrade Soils Investigation

Soil borings and sampling have been used in combination with GPR to refine and verify the results of GPR. The subgrade investigations for the various new track construction projects ranged from soil boring and sampling over a considerable depth, to shallow excavation and visual/manual inspection of the subgrade at its upper surface. Of course soil boring at depth is preferable to a shallow subgrade investigation because the former determines the soil layer thickness, soil types, soil firmness as measured by SPT (standard penetration test) blow counts, and soil moisture conditions over this depth. If soil information at depth is required, an approach that is more efficient than soil borings is using the Cone Penetrometer test (CPT). This test involves an instrumented cone to measure the resistance (stiffness) of the soil continuously with depth that can be correlated directly with soil strength and soil type to provide a more detailed assessment of the soil layers and their properties. This method is particularly valuable for its use with the granular layer thickness design method as described below.

Although the visual/manual inspection of the top of the subgrade through very shallow subsurface investigations did not provide highly detailed soil assessments, they did provide the basic information needed to design track with limited subgrade deformation, such as the depth of the subgrade soil layer under the roadbed surface, the subgrade composition, and the subgrade stiffness.

Use of Existing Roadbed Materials as Ballast/Subballast in New Track Construction

Before new track can be constructed on the existing roadbed, excavation of the roadbed is generally required to provide an area for sufficient subballast and ballast. All cut material must be transported away and disposed of at considerable cost if it could not be reused as ballast and/or subballast in the new track construction. Therefore, to reduce costs, Amtrak sampled the old roadbed for gradation analysis to determine if this material was suitable for reuse. It was determined that the roadbed ballast gradation is within the range of acceptable gradation limits for subballast, provided that the material greater in size than 1.5 inches are removed. The material larger than 1.5 inches will be combined with new ballast to reduce the quantity of new ballast required. Screening of the old roadbed on a 1.5-inch sieve will be done on site to minimize the movement of material. Laboratory testing used by Amtrak includes LA Abrasion for ballast reuse and new ballast, unconfined consolidation strength for soil slope testing, and grainsize analysis/identification for roadbed and soils.

The determination that the existing roadbed material could be used for ballast and/or subballast for the newly constructed track provides considerable savings by reducing the “up-front” costs of construction. The costs in the future of repeated geometry correcting maintenance were also minimized by using a design procedure to select the granular layer thickness (ballast plus subballast) to limit subgrade deformation to the tolerably small amount on the order of one inch as described in the next section.
Use of the Granular Layer Thickness Design Method

Conventional ballasted track construction in the US often uses uniform, nominal layer thicknesses of approximately 12 inches of ballast and 6 inches of subballast. However, choosing these layer thicknesses because they are “industry standard” without regard to whether the subgrade will be overstressed for the loading applied cannot be referred to as a proper design approach, it is merely following a practice. Higher capacity track requires a stronger roadbed than conventional track. For track with reasonably strong subgrade soil the practice of using a combined ballast and subballast granular layer of approximately 18 inches may be adequate, but locations with soft subgrade will experience significant track settlement and geometry roughness which can drive up life-cycle costs considerably, especially with increased speeds and traffic.

The Granular Layer Thickness (GLT) design method (Li and Selig, 1998) provides the most comprehensive procedure available to determine the required combined granular layer thickness of ballast plus subballast between the subgrade and the tie bottom. With knowledge or reasonable estimates of a few key parameters shown in Figure 7 relating to subgrade soil type, subgrade strength, subgrade stiffness, ballast stiffness, and traffic loading, the required thickness of granular material (H) over the subgrade can be reliably determined. This design approach is superior to the AREMA recommended practice of dimensioning this layer based on an assumed allowable vertical stress of 25 psi on the subgrade surface which for many soils assumes too high a subgrade strength. In addition, future increases in traffic, number of tracks, loads, and speeds affect layer thickness and can be incorporated in the design.

![Figure 7 Simplified representation of granular layer and subgrade](image)

The GLT method is based on a mechanistic model that considers the two most common subgrade failure modes of 1) subgrade squeeze and 2) ballast pocket formation as shown in Figures 8 and 9 respectively. Subgrade squeeze failure initiates in a fine-grained soil, typically clay, shearing at the point of maximum loading stress which is usually directly below the end of the tie as shown in Figure 8. As this failure progresses and the zone of failed subgrade grows, the remolded soil is squeezed up and outward as the track geometry error grows. The ballast pocket subgrade failure in Figure 9 results from soil deformation that occurs not just at the surface as the subgrade squeeze does, but also from vertical soil deformation over a thicker
subgrade layer. Design charts from the Li and Selig design method are used to determine which failure mode governs design by virtue of requiring the thicker granular layer.

Figure 8. Subgrade progressive shear failure mode (subgrade squeeze)

Figure 9. Excessive subgrade plastic deformation failure mode (ballast pocket)

The GLT design procedure also considers the mix of traffic loading with its distribution of axle load magnitudes and the number of load cycles ranging from passenger to heavy-axle traffic. The resulting granular layer is of sufficient thickness to limit subgrade deformation to a tolerably small amount of one inch that occurs over the life of the track which was assumed for these projects to be 30 years. Use of this design method showed that for Amtrak’s new track construction projects, the minimum required GLT was 16 inches for one project and 24 inches for another in order to limit subgrade deformation in both cases to approximately one inch over the track life of 30 years. By contrast, if the more typical industry standard GLT of 18 inches had been used rather than 24 inches as required using the GLT design for one project, the track deformation over the track life would have been significantly more than one inch which would require much more maintenance, shortening the track life, and driving up life-cycle costs.
Lastly, this design method avoids an overly conservative selection of the GLT where a thinner layer will suffice. A thinner granular layer will provide the added benefit of less required track width where right-of-way access is limited and where the ballast toe might encroach on an embankment slope.

Potential Use of Cone Penetrometer Test (CPT) to Determine Granular Layer Thickness

As mentioned previously, the CPT is a better method than performing soil borings with blow counts to characterize the soil layers with depth. Additionally, the parameters shown in Figure 7 that are needed for the GLT design method can be readily obtained using the CPT. When the instrumented cone is on the ballast surface and is pushed into the subgrade, the resulting instrumented cone measurements can provide the ballast stiffness ($E_b$), the subgrade soil type, strength ($\sigma_s$) and stiffness ($E_S$), and the thickness of the soft soil layer (T).

Ballast Life Calculation

The ballast life-cycle cost calculation can further reduce costs by choosing ballast that provides a long life with a slow rate of material breakdown and minimal required maintenance. The ballast materials considered had a relatively low allowable abrasion loss (Los Angeles Abrasion limit = 18%) which for the imposed loading estimated during the track life gave a ballast life of approximately 700 MGT for a twelve inch thick (under tie) ballast layer. This was estimated based on the ballast breakdown rate from traffic loading combined with the amount of breakdown due to tamping applications that occur over the track life of 30 years.

Challenges Encountered During Design

Slopes

Designs for fills along existing track, and new track must assure that a steep slope just off the end of the ballast shoulder does not result in a loss of material below the tracks as shown in Figure 10. Note how the aerial view in Figure 10a indicates that material below the tracks has been sliding into the water and produced a change in water color from the underwater “plume” of material local to the failure. Figure 10b shows the steepness of some slopes and their inability to retain a ballast shoulder.

Figure 10a) Overhead photograph of unstable ballast shoulder, 10b) Oblique view of same
These conditions are to be repaired by providing barrier walls or widening the embankment top. In cases where the roadbed width could not be widened sufficiently to accommodate the new track due to encroachment on wetlands, retaining walls were designed to provide the required 3-foot walkway off the toe of the ballast shoulder as shown in Figure 11.

Figure 11. Barrier walls constructed where added embankment width would have encroached on wetlands

The existing substructure problem conditions that must be remedied at the location shown in Figures 10a and 10b were determined by GPR and are shown in Figure 12a. A strategy proposed for their remediation is shown in Figure 12b.

Figure 12 a) Ballast Pocket in Soft Subgrade Location Found by GPR, b) Proposed Remediation

Drainage

A number of cut area locations had poor drainage such as the location shown in Figure 13 with the corresponding substructure conditions indicated by the GPR in Figure 14a. Note that in addition to inadequate ditches and insufficient longitudinal slope of the ditch, there are also poor
internal drainage conditions due to lack of a lateral escape path for water trapped in the roadbed. The proposed remedy is shown in Figure 14b.

Figure 13. Example of Poor External Track Drainage

Figure 14a Corresponding Poor Internal Track Drainage, 14b Remediation of Drainage

Summary and Conclusions

Amtrak has met the challenges encountered in designing new track construction over old roadbed by using some of the latest developments in design procedures and substructure
measurement tools. In particular the ground penetrating radar (GPR) measurement system was used to find locations of potential instability due to the presence of pre-existing locations with soft subgrade deformation (ballast pockets) that must be stabilized and excess water that must be drained before track construction. The costs of construction were reduced by the determination that some of the existing ballast and subballast sized material in the old roadbed could be combined with new ballast and subballast, reducing disposal costs and the amount of new material required. A cost savings was also provided over the life of the track by designing it to withstand increased traffic and speeds with only minimal deformation and geometry correcting maintenance, resulting in low life cycle cost. Despite the considerable challenges presented by roadbed that was built in the 1800’s, Amtrak was able to cost effectively design new durable track on old roadbed using a number of modern tools and design methods.

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References

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AMTRAK
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What Lines Are We Talking About?

- Older lines being adapted for higher speeds
- Proposed speeds up to 110 MPH
- In the east, many old lines are in densely populated areas
- Many lines in heavily developed areas
- Some lines had tracks removed during “downsizing” era
- Lines generally have mixed traffic
- Lines not grade separated

Focus Today

COST-EFFECTIVE ROADBED DESIGNS

- Roadbed section - numerous challenges of adapting new track to old roadbeds
- Roadbed strength - assessment and identification of unstable areas
- Roadbed drainage - assessment and identification of poorly-drained areas
- Granular layer thickness design (GLT) - application for effective and economical track support

Issues with Reuse of Old Roadbeds

- Narrow rights-of-way
- Built with few, if any environmental restrictions
- Roadbed sections based on obsolete standards
  - Track and ballast sections less robust
  - Limited by construction methods available at the time
  - Construction access was by motorcar, not by vehicles
- Materials used for roadbed construction
  - Limited length of haul meant use of local materials
  - Build them now, fix them later
  - Granular layers are composed of old materials
  - Non-uniform
  - Life expired

Adapting New Track to Old Roadbeds

Issues posed by access road:
Adapting New Track to Old Roadbeds

Restrictions posed by existing cuts and fills - need extra width

Retaining wall and 3-ft access space needed to not encroach on wetlands and ROW:

Need fill for wider track spacing:

Use slope analysis to establish actual slope requirements
Use borings where necessary to establish strength of soils
Use walls where necessary
  - To stay within rights-of-way
  - To avoid wetlands
Use flood frequency to establish actual drainage requirements
Get widest track centers possible
Use at least 3-foot shoulders for passenger and roadway worker access

Finding and Remediating Existing Substructure Problems - Tools and Methods

LIDAR for Surface Topography, Drainage
Ground Penetrating Radar (GPR)

GPR Indicating Ballast Pocket Formation

“Hotter” colors indicate deeper ballast and deformed subgrade

Track Geometry Data Complements GPR

Example of Existing Roadbed Instability

Example - Remediating Existing Roadbed Problem

Remediating Roadbed Problems

- Use all the tools at your command to diagnose
  - GPR
  - LIDAR
  - Use of existing track geometry
  - Subsurface investigations - borings, test pits, CPT
  - Laboratory testing
  - Site reconnaissance
  - Engineering studies - i.e. slope analysis, reports
Remediating Roadbed Problems (continued)

- Use all the tools at your command for remediation - proper fix from proper diagnosis
  - Modern materials
    - Geoweb
    - HMA
  - Big guns when necessary
    - Piling
    - Walls
- Very often related to drainage problems!

Example of Existing Roadbed Drainage Problem

Bathtub effect - retained water:

Example - Remediating Roadbed Drainage Issue

Existing Conditions:

Clean Shoulder to Longitudinal Sub-Drain, Open Ditch or Fill Slope

After Remediation:

Provide adequate depth for pipe to have proper longitudinal slope

Remediating Drainage Issues

- Look at flood frequencies to identify what is cost effective
- Look at areas where topography does not give adequate pitch to move water
  - Use underdrains to help
  - Allow water to leave right-of-way
- Increase number of cross-drains if necessary
- Use all the tools at your command to diagnose the problem by identifying the sources of water entry

Granular Layer Thickness (GLT) Design

Granular layer is combined thickness of ballast, subballast, and any existing strong granular roadbed that is over the subgrade:

Granular Layer Thickness (GLT) Design for New Track

Granular layer

Deformable subgrade layer

Rigid layer
GLT Design to Prevent Squeeze

- Design method limits stresses on subgrade surface to prevent this progressive failure:

Squeeze is forming
Advanced subgrade squeeze

GLT Design to Prevent Ballast Pockets

- Design method limits stresses within subgrade layer to prevent this failure:

Analysis of Existing Roadbed Material...

...showed it could be used as subballast in GLT design which avoids potential mismatch of track elevation as shown:

GLT includes partial depth of existing roadbed, reducing amount of new material needed

GLT Design Summary

- Use ballast life/thickness models
- Use existing material to provide part of necessary thickness where possible
  - Especially on old main track roadbeds
  - Do sieve and material analysis to determine suitability
  - May be able to rescreen or crush material for subbase
  - Make sure subgrade does not contain water traps

GLT Design Summary (continued)

- Minimize GLT where possible
  - Reinforce if necessary
  - Avoid removal of excess material and generating a disposal issue
  - Make sure resulting design provides uniform support

Summary - Methodology

- Identify rights-of-way plus environmental restrictions
- Determine what combination of tools and methods to use
- Sample and characterize existing roadbed, subgrade, slope, and groundwater conditions
- Determine the trade-offs to the most cost-effective design solution
## Summary - Tools for Evaluation

- Site reconnaissance
- GPR
- LIDAR
- Use of existing track geometry data
- Subsurface investigations- borings, test pits, CPT
- Laboratory testing
- Engineering studies- slope evaluations, flood data

## Conclusions

- The tools and methods allow for the proper diagnosis of roadbed problems
- Tools work best if used in combination
- The proper diagnosis allows for the analysis of design trade-offs with problem areas
- The most cost-effective design gets the highest utility for the dollar spent, while providing for a safe operation