ABSTRACT

The RailJET® is a hi-rail subgrade stabilization system that installs soil cement rigid jet grouted columns below the track structure (Figure 1). These columns transfer track bed loading deeper into the subgrade strata to more stable bearing material. The application and design for these columns improve a suite of problems experienced by railroads along their track structure such as subgrade settlement, embankment instability, lateral spreading, bearing capacity failures, and saturated fouled ballast pockets. The system works on existing track under defined work windows without lasting outages or removing track structure. The RailJET® system is fully self-contained and operates under its own power without the need for a flat car or railroad provided equipment. The system can access the track from any 50-foot wide roadway or temporary crossing. No material is wasted during column installation because grout mixtures are combined at the point of injection and continuously mixed as work progresses.
the advantages of the RailJET® system over conventional remediation methods including, accessibility, railroad support requirements, production, performance, logistical benefits, and improvements going forward.

INTRODUCTION TO SUBGRADE INSTABILITY

One of the most challenging maintenance problems railroads across the United States and the world face is track bed instability, and the best description of subgrade failure is a bearing capacity failure of the supporting soil below the track bed. The visible manifestations of these problems are well known and easy to identify. Symptoms such as tie deterioration, ballast degradation, mud pumping through track ballast, misaligned track, and hard switch transitions are all indicators of poor track bed performance (Guenther, 2009). Typical maintenance measures for these conditions are very intuitive. Track ties are replaced when they deteriorate, fouled ballast is cleaned or replaced, misaligned track is realigned to proper geometry; often adding additional ballast to achieve it. All of these measures restore track to normal service, but do not treat the problem’s root cause.

Poorly performing subgrade conditions are often the initiating reason for the visible track maintenance problems described above. While all of the standard maintenance measures implemented by railroads to treat these conditions restore track service and geometry, they do nothing to address subgrade instability. In some cases, the common maintenance activity exacerbates the problem; increasing frequency of future necessary maintenance work. Trackbed subgrades become unstable for several reasons and include poor drainage, poor ditch maintenance, over-steepened embankment geometry, and poorly compacted subgrades placed after maintenance or emergency construction activities.

![Figure 2. Subgrade Instability observed as track differential settlement, mud boils and geometry defects.](image)

Train loads are distributed through the rail, tie plates, ties, ballast, and sub-ballast to reduce the overall pressure applied to the subgrade. However, a saturated clay subgrade’s bearing capacity is often inadequate to resist this pressure, which leads to failures. Failure mechanisms include shoulder heave, lateral spreading, and liquefaction of the soil that migrate through the ballast and present themselves as mud boils in the track. This failure also results in ballast pushing farther down into the subgrade creating ballast pockets that hold water and keep the subgrade in a constant saturated state (e.g. perched water pockets within the embankment). Adding ballast to remedy track geometry issue in these situations deepen ballast pockets and increase the severity of the problem until a more severe failure may occur such as a sudden derailment or broken rail.

CURRENT SUBGRADE INSTABILITY REMEDIATION WORK

The concept of subgrade treatment to improve track bed stability is not unknown to the railroad industry, and many methods have been implemented over the years. The most rudimentary treatment is to over-excavate the unsuitable subgrade soils and replace them with adequately compacted material that is less susceptible to absorption. This solution is useful but very invasive and interrupts train service. Depending on the size
of the soft subgrade problem along the track structure and the volume of train traffic, over-excavation may be very costly and unfeasible. One effect of Class 1 Railroads in the US implementing Positive Train Control (PTC) systems over the last decade is an increased density of train traffic. Shorter intervals between trains mean less time for maintenance work; especially work that removes the track from service.

Other less invasive measures include installing layers of geogrid, geotextile, or geocells (Musgrave, 2017) within or below the immediate subgrade layer to improve stiffness and bearing capacity. These tools, when properly designed and installed, are effective in enhancing subgrade response. Hot-mix asphalt underlayment started in in the early ’80s (Rose, 2017) as a replacement or partial replacement for sub-ballast as means of improving track bed stiffness / performance with success.

All of these methods are very conducive to new track construction or existing track remediation where the existing track structure can be temporarily removed for installation. However, the methods are often not feasible with increasing train traffic, traffic density, and track speeds. Smaller sections of track need to be removed when windows are limited to reduce the daily work time and these actions increase project costs and overall duration.

![Figure 3. Geocell installation (left) and Asphalt underlayment (right) as a means of treating soft subgrades below track structure (Musgrave 2017), (Rose 2017).](image)

**RailJET® Subgrade Stabilization**

GeoStabilization International® (GSI®) designed and developed a means of treating bearing capacity deficiency in existing track subgrades by creating the RailJET® hi-rail injection system (Figure 1). RailJET® is a modified jet grouting process intended specifically for railroad subgrade stabilization that uses a high-flow, horizontal jet of fluid to mix existing soil with a cementitious slurry. It is a hydrodynamic mix-in-place technique producing soil-cement columns, or rigid inclusions, to reinforce the soil both in bearing and shear. The diameter of the inclusions is dependent on actual in-situ soil conditions; however, it is a minimum of 6 inches in width with some columns extending up to 20 inches in diameter.

The overall result of the column installation is graphically illustrated in Figure 4. The RailJET® equipment consists of a drilling unit, and a mixing unit, allowing all the work to be accomplished from the railway platform. The drill truck and mixing trailer have independent track travel power units and are interconnected when the equipment is working. This construction allows for redundancy in track travel capabilities in the event on power unit malfunctions.

The treatment depth can extend up to 30-feet below the “top of tie” surface with varying patterns and density depending on the subgrade conditions. The treatment method is a form of ground improvement utilizing cement jet grouted columns as a means to transfer track bed loading deeper into the subgrade strata to more stable bearing material. The application and design for these columns improve a suite of problems experienced by railroads along their track structure such as subgrade settlement, embankment instability,
lateral spreading, bearing capacity failures, and saturated fouled ballast pockets. Equipment performance specifications were adapted from ASCE G-I Committee – Jet Grouting Guide Specifications to meet this specific rail objective.

![Figure 4. RailJET® Treatment Illustration before and after installation.](image)

The system works on existing track under defined work windows without lasting outages or removing track structure. The RailJET® system is fully self-contained and operates under its own power without equipment support from the railroad. The RailJET® can access the track from any 50-foot wide roadway or temporary crossing. No material is wasted during column installation because grout mixtures are combined at the point of injection and continuously mixed as work progresses. In most cases, 100% occupancy of the track is returned to the Railroad as soon as the equipment clears to a siding or spur track.

RailJET® drill truck contains a single mast with two independent drilling heads. The drill heads can have lateral adjustment capabilities allowing for columns to be installed from the outside edge of tie to just inside the gauge of the rail. Up to 4 columns can be installed per tie crib location. Each injection installs two columns (two drill heads) in 5 to 15 minutes depending on drilling conditions and depth of columns installation. As stated above, cement is mixed on demand with a dry cement silo and water tanks built into the mixing trailer which reduces waste and increases efficiency.

Once the desired treatment zone is completed, any remaining dry cement in the silo is removed along with remaining water in the storage tanks. The entire system then dismounts the rail at the nearest suitable crossing and prepares for road travel to the next location. The system lends itself to recording and providing exact installation as-built drawings with injection locations and depths detailed. This location information is vital for subgrade treatment work because there are little known visual indicators of where subgrade treatment work was completed after it’s finished. The precise record keeping helps railroads keep an inventory of treated zones so they can track performance and durability. Example treatment as-built drawings are shown in Figures 5a and 5b.
Design Methodology

A patent-pending design method for RailJET® subgrade treatment was developed in 2017 and includes a combination of ground improvement design, track component configuration, track loading, and damage criteria as parameters.

A two-phased approach to selecting the appropriate subgrade treatment is taken. The first consideration is the treatment effort required to provide global stability against bearing capacity failure, excessive deflection, etc. The second consideration relates to selecting a design life for the subgrade treatment and assessing the suitability of the proposed treatment through a series of damage analyses.

The type of subgrade soil is determined either by field inspection or geotechnical explorations. Representative parameters for these soils including, shear strength, ultimate bearing capacity, unified soil classification, and fines content are assumed or determined from laboratory testing. This information combined with the jet grouting equipment specific to the RailJET® system allows for column diameter estimation and optimal pattern design. Subgrades requiring treatment often consist of high plasticity clays with low shear strength as these types of soils often exhibit the bearing capacity problems described in this paper. Key soil parameters that are most beneficial in this process include Atterberg limits, in-situ moisture content and grain size analyses testing.

The estimated column diameter and known injection volumes / pressures specific to the RailJET® equipment allow for the column design compressive strength to typically range from 200 to 600 psi. Column size and compressive strength combined, with the in-situ soil strength properties are used to determine composite soil shear strength achieved through the treated zone. This methodology is similar to rammed aggregate piers or granular columns which are commonly used in ground improvement design (Lawton & Fox 1994). This approach begins by assuming an area replacement ratio of column to native matrix soil as well as the relative stiffness modulus ratio of the column to the matrix soil. The composite shear strength envelop is then estimated for the improved subgrade soils. The resultant design provides the new ultimate bearing capacity estimate of a foundation supported by a group of reinforcing columns as shown in Figure 6.
Long-term serviceability of the RailJET® improved subgrade soils is assessed through a combination of numerical analyses consisting of load-deformation and multilayer-elastic damage cycle analyses computer programs. Numerical analyses were performed to compare the influence of the ground improvement. The excerpt below demonstrates the XY-Strain from a cycle of E-80 loading with and without ground improvement. The model demonstrates considerably less strain within the improved subgrade.

The computer program KENTRACK, developed by the University of Kentucky, has also been utilized to estimate the service life of the trackbed based upon the rail and tie type and weight, estimated train loading and traffic, among other factors. This assessment has been found to agree with the finite-difference load deformation analyses presented above.
RailJET® Project Performance and Review

The equipment development and construction processes were completed in April 2017. Since then the RailJET® System has completed subgrade and embankment treatment projects for most of the Class 1 railroads in North America as well as some selected Shortline Railways. The following present some recent past case studies that represent the versatility of the RailJET®.

Case Study 1 - Track over Soft Peat Subgrade (40 MPH, 20 to 30 Trains / Day)

Railway representatives reported that after RailJET® treatment of over 300 track feet that the track surface has been holding since work completion. Before treatment, this section of track, which included a main switch and bridge approach, had to be maintained on a daily basis to stay in service. Work at this location completed in June of 2018. This project was especially challenging given the track bed consisted of 9-feet of ballast from years of track maintenance and surfacing work and the track embankment was only 3 to 4 feet high. The thick ballast section was heavily compacted and fouled which presented a challenge for drilling and slowed production. Columns extended 30 feet below tie elevation at this location through the ballast and underlying 15 to 20-foot thick layer of organic peat. This is likely the most challenging subgrade condition treated to date. Treatment patterns used for this project were adapted to each location and generally followed one of the three patterns shown in Figure 8.

Logistical advantages proved to be a contributing factor to project success at this location. Track time was minimal with only 3 to 4-hour windows per day which were sometimes broken up into multiple shorter windows. The ability to change locations with short notice while minimizing waste, accessing the track at crossings, not requiring a railroad-provided flat car to perform the work and leaving a clean work site were the clients’ primary concerns after safety and treatment performance. The RailJET® system excelled at all of these criteria.

Figure 8. Treatment Patterns used for varying ground conditions for projects near International Falls, MN.

Figure 9. RailJET® Injection Equipment.
Case Study 2 - Track over expansive clay subgrade.

This project included a mile of subgrade treatment as part of a comparison test with other methods. The railroad contracted with three different contractors to perform three different modes of subgrade treatment in succession through similar ground conditions to evaluate which method provided the best overall performance. We were told the criteria for performance included, project cost, project duration, treatment performance, and contractor performance. The RailJET® system was selected as the best overall value at the conclusion of this comparison, and three more treatment projects are scheduled as a result of this evaluation. To date, the treated area has not needed to be resurfaced since the project was completed nearly 1 year ago.

Logistical performance and efficiency were the primary advantages realized at this project. On track equipment, with a fast ability to mobilize to and from work locations, with short windows and warnings between trains proved to optimize work efficiency and minimize impacts on train traffic. The railroad reported that the subgrade performance through the RailJET® treated area was also performing the best of all the treated sections.

Case Study 3 - Curved track next to lake.

This project involved stabilizing a section of track situated in a curve along a Class 1 mainline track that parallels a protected lake. Based upon the results of the subsurface exploration and our global slope stability analyses, the live load was primarily responsible for causing the noted track movement. As such, a very dense RailJET® pattern was selected for this section of track in an effort to create a grade bridge through the curved area. This treatment was successfully able to stabilize the trackbed by transferring the loads past the existing failure plain. The project was also permittable by the USACE due to the minimal impact on the adjacent lake.

Figure 10. Typical view of curved mainline adjacent to lake.
Concluding Remarks and Planned Improvements

The RailJET® subgrade treatment system was developed with several objectives and criteria in mind. The most important were:

- Crossing accessibility to mount and dismount the track
- Self-contained equipment that required no railroad-owned support equipment
- Continuous mixing to reduce waste and increase flexibility with varying track time
- 30-feet of treatment depth
- Performance and reliability of the treatment and equipment.

Almost all of these objectives were met with the first-generation system as constructed. The RailJET® equipment, patent-pending design methodology, and installation process have been greatly successful since 2017. Railroads are reporting the treatment is working, and the logistics of working with the equipment are an improvement over other existing industry technology.

Advances going forward will be adjustments to improve equipment efficiency, durability and maneuverability. Engineering developments will also be made in regard to collection of empirical data relating to the performance of the RailJET® level of improvement in various soil types and applications. Quality controls will continue to be implemented to obtain real-time measurements during construction in an effort to assess changes in ground conditions along the alignment.

REFERENCES


Title: RailJET®: Soft Subgrade and Embankment Stabilization, Introduction of New Hi-Rail Technology for Subgrade Maintenance.

Presented By:

Justin Anderson, PE
GeoStabilization International

and

Kyle Guenther, PE
GeoStabilization International
Soft Subgrades:

- Unsuitable material used for trackbed construction.
- Poor Compaction or subgrade treatment prior to construction
- Poor drainage causing constant saturated conditions!!

Effects:

- Bearing Capacity Failure of Subgrade soils
- Track Profile defects and differential settlement
- Track delays / slow orders decrease capacity and efficiency
- Maintenance costs, equipment and crew resources are allocated to problem areas, neglecting normal maintenance.
- Potential for Derailments and track outages.
Typical Solutions for Soft Subgrades

- Undercutting and releveling the track. Restores track Geometry and removes defects that cause slow orders or track outages. (Treats the symptom not the illness)

- Treating the cause can improve performance and significantly reduce ongoing maintenance needs

- Undercutting Replaces Fouled Ballast with Clean Ballast up to 12 inches below the ties, doesn’t address how the ballast became fouled in the first place.
Typical solutions for Soft Subgrades

- Over Excavation of the poor material and replacement with more suitable soils.
- Installation of Geotextile Layers, GeoCells, Asphalt Underlayment to improve bearing capacity.

These methods can be effective to replace poor material or distribute loads over poor underlying material more efficiently.

- Requires long track outages and depending on location may not be feasible with adjacent access.
The Problem

Saturated Embankments or Poorly Compacted Repairs

• Trapped Water within the embankment ballast pocket keeps the embankment saturated.
• Saturated embankments experience:
  • Mud Pumping through the Ties
  • Slope Instability
  • Bearing Capacity Failures
  • Lateral Spreading
• Poorly Compacted Embankment Repairs or culvert installations lead to track settlement of the loose or unconsolidated material.
• Settlement followed by adding ballast for geometry repairs develops Ballast Pockets.
Railroad Embankment Stabilization and Drainage improvement

Trench Drains

- Treats the root cause of clay embankment settlement and instability instead of symptoms.
- Removes trapped water from the track bed and releases hydrostatic pressure on slopes.
- Stiffens embankment sections with spaced columns of angular ballast rock.
- Allows the embankment clays to support the track in a drained condition.
Typical Solutions for Saturated Embankments

- Intercept the Ballast Pocket
- Trench Drain Excavation
- Remove Water From The Embankment
Embankment Trench Drain Installation

ALLOW TRAPPED WATER TO ESCAPE THE BALLAST POCKET
ALLOW TRAPPED WATER TO ESCAPE THE BALLAST POCKET
Typical solutions for Saturated Embankments

- Flatten embankment slopes / improve ditch conditions
- Rebuild embankments using more suitable soils and better compaction.
- Armor slopes with riprap or driven timber piles
GSI’s RAILJET™ Technology Offers an Economical and Efficient Means of Improving the Stability of Soft Subgrades and Reducing Maintenance Costs with Limited Impact to Railway Traffic or Operations

- Treats the cause of settlement by improving/stiffening soils under the ballast/embankment
- Fills ballast pockets
- Treatment from directly below clean ballast up to 30 ft deep
- Reduces long term maintenance needs such as releveling and undercutting
• RailJet inclusions (cement grout mixed with in situ soil) are a form of ground improvement

• Approximately 8 to 12 inches in diameter but depend on in situ soil conditions, the weaker the soil, the larger the diameter

• Generally 10, 20 or 30 ft deep (the diameter depends on the stiffness of the soil)

• Two columns are created at a time, and in very weak subgrade soil conditions, the rig will produce 2-column rows of these columns along the track to be stabilized, then go back and install two additional column-rows for added strength and support.

• The method allows creating a column every tie, every second tie, every fourth tie etc., and creates them in pairs of two

• Increase subgrade bearing capacity and shear strength

• Fill deep ballast pockets with cemented soil (150 to 500 psi), will not hinder future track or subgrade work
• In areas where train traffic is critical, the grout is accelerated so that the column will gain initial set in 30 minutes to 2 hours depending on dosages, and traffic windows

• The columns will not be degraded by train traffic within the initial cure period

• The grout will not foul clean ballast

• There is no waste product because the material is mixed real-time within minutes of being pumped in the ground

• The top of the RailJet column is terminated at the bottom of the clean ballast, usually 3 ft below track to ensure the track bed loads are distributed over the column array and prevent over stressing individual ties or track work; this depth can be adjusted to specific ground conditions or railroad preference

• All the equipment is hi-rail mounted and self-sufficient, and will be able to access the rail at most two lane crossings similar to a hirail dump; no support other than track protection is required from the RR

• Track surfacing may be necessary following treatment to reshape ballast depending on the required spacing for the column array
• RailJet can reduce dynamic loads on bridges and bridge abutments

• Bridge transitions can be improved using this method by gradually increasing the column array density and depth as rail approaches the bridge

• This will gradually increase the subgrade strength approaching the bridge and ease the stiffness differential between the track embankment and the bridge structure
Hi rail trailer
Cement silo
RailJET grout mixer and pump
Diesel electric generator
Hi-rail drill truck
Drill masts
Water tanks
Part of the locomotion of the trailer
Part of the cement silo
## Typical subgrade parameters

<table>
<thead>
<tr>
<th>Soil #</th>
<th>USCS</th>
<th>Unit Weight</th>
<th>CBR</th>
<th>Su (psf)</th>
<th>Es (psi)</th>
<th>Qu (psf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH/CL</td>
<td>115</td>
<td>0.5</td>
<td>116</td>
<td>1,636</td>
<td>1,130</td>
</tr>
<tr>
<td>2</td>
<td>CH/CL</td>
<td>118</td>
<td>1.5</td>
<td>348</td>
<td>3,305</td>
<td>2,035</td>
</tr>
<tr>
<td>3</td>
<td>CH/CL</td>
<td>120</td>
<td>2</td>
<td>465</td>
<td>3,973</td>
<td>2,630</td>
</tr>
<tr>
<td>4</td>
<td>CH/CL</td>
<td>122</td>
<td>3.25</td>
<td>755</td>
<td>5,421</td>
<td>4,100</td>
</tr>
<tr>
<td>5</td>
<td>CL</td>
<td>122</td>
<td>5</td>
<td>1,161</td>
<td>7,142</td>
<td>6,206</td>
</tr>
<tr>
<td>6</td>
<td>CL</td>
<td>122</td>
<td>10</td>
<td>2,323</td>
<td>11,130</td>
<td>12,179</td>
</tr>
<tr>
<td>7</td>
<td>CL</td>
<td>122</td>
<td>20</td>
<td>4,645</td>
<td>17,344</td>
<td>24,119</td>
</tr>
</tbody>
</table>
RAILJET™ Column Diameter

The Diameter of RailJET Column can be estimated more accurately using the following key soil parameters:

- Ultimate bearing resistance of soil
- Content of fine particles less than 75 μm as a percentage
- Average size of soil particle

<table>
<thead>
<tr>
<th>Soil #</th>
<th>USCS</th>
<th>Unit Weight</th>
<th>CBR</th>
<th>Su (psf)</th>
<th>Es (psi)</th>
<th>Qu (psf)</th>
<th>Assumed Column Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH/CL</td>
<td>115</td>
<td>0.5</td>
<td>116.13</td>
<td>1,636</td>
<td>1,130</td>
<td>18-24</td>
</tr>
<tr>
<td>2</td>
<td>CH/CL</td>
<td>118</td>
<td>1.5</td>
<td>348.39</td>
<td>3,305</td>
<td>2,035</td>
<td>16-22</td>
</tr>
<tr>
<td>3</td>
<td>CH/CL</td>
<td>120</td>
<td>2</td>
<td>464.52</td>
<td>3,973</td>
<td>2,630</td>
<td>14-20</td>
</tr>
<tr>
<td>4</td>
<td>CH/CL</td>
<td>122</td>
<td>3.25</td>
<td>754.84</td>
<td>5,421</td>
<td>4,100</td>
<td>12-16</td>
</tr>
<tr>
<td>5</td>
<td>CL</td>
<td>122</td>
<td>5</td>
<td>1161.29</td>
<td>7,142</td>
<td>6,206</td>
<td>8-14</td>
</tr>
<tr>
<td>6</td>
<td>CL</td>
<td>122</td>
<td>10</td>
<td>2322.58</td>
<td>11,130</td>
<td>12,179</td>
<td>6-10</td>
</tr>
<tr>
<td>7</td>
<td>CL</td>
<td>122</td>
<td>20</td>
<td>4645.16</td>
<td>17,344</td>
<td>24,119</td>
<td>-</td>
</tr>
</tbody>
</table>
Composite soil shear strength envelope

Figure 5.22: Barksdale and Bachus' (1983) method to estimate the ultimate bearing capacity of a foundation supported by a group of reinforcing columns.

## Composite soil shear strength envelope

### Φ<sub>comp</sub> (deg)

<table>
<thead>
<tr>
<th>Case</th>
<th># Columns</th>
<th>Frequency</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>32.6</td>
<td>32.2</td>
<td>31.7</td>
<td>28.4</td>
<td>26.3</td>
<td>18.0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>30.7</td>
<td>30.0</td>
<td>29.0</td>
<td>23.9</td>
<td>20.9</td>
<td>12.0</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>29.0</td>
<td>28.0</td>
<td>26.8</td>
<td>20.6</td>
<td>17.3</td>
<td>9.0</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
<td>33.3</td>
<td>33.3</td>
<td>33.2</td>
<td>33.1</td>
<td>30.0</td>
<td>32.5</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
<td>32.6</td>
<td>32.2</td>
<td>31.7</td>
<td>28.4</td>
<td>26.3</td>
<td>18.0</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>31.7</td>
<td>31.1</td>
<td>30.3</td>
<td>26.0</td>
<td>23.3</td>
<td>31.1</td>
</tr>
</tbody>
</table>

### C<sub>comp</sub> (psf)

<table>
<thead>
<tr>
<th>Case</th>
<th># Columns</th>
<th>Frequency</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>96,722</td>
<td>60,401</td>
<td>39,985</td>
<td>12,884</td>
<td>8,935</td>
<td>4,804</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>25,410</td>
<td>19,116</td>
<td>14,623</td>
<td>6,159</td>
<td>4,764</td>
<td>3,532</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>15,048</td>
<td>11,470</td>
<td>9,088</td>
<td>4,232</td>
<td>3,506</td>
<td>3,122</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1,041,014</td>
<td>873,920</td>
<td>379,425</td>
<td>312,684</td>
<td>19,624</td>
<td>77,843</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
<td>96,722</td>
<td>60,401</td>
<td>39,985</td>
<td>12,884</td>
<td>8,935</td>
<td>4,804</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>39,844</td>
<td>28,946</td>
<td>21,312</td>
<td>8,232</td>
<td>6,085</td>
<td>29,792</td>
</tr>
</tbody>
</table>
Immediate benefits

- Increase in subgrade bearing capacity
- Increase in shear strength
- Reduced settlement potential
- Reduced subgrade “pumping” potential
- Ballast pockets filled
<table>
<thead>
<tr>
<th>Case</th>
<th># Columns</th>
<th>Frequency</th>
<th>Ultimate Bearing Capacity (psf)</th>
<th>Column Depth (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>498,050</td>
<td>498,050</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>130,902</td>
<td>130,902</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>77,555</td>
<td>77,555</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
<td>5,359,742</td>
<td>5,359,742</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
<td>498,055</td>
<td>498,055</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>205,219</td>
<td>205,219</td>
</tr>
</tbody>
</table>
Long-term benefits

• Reduced dynamic loading on structures such as bridges
• Less maintenance such as resurfacing and undercutting
• Reduction in slow orders & outages
• Faster operating speeds
• Less Track Deflection
  • Less working of plates and ties
  • Less deflection of rail
• Longer Service Life of Track
Load Deformation Analyses

- Use Computer Program SIGMA/W by GeoStudio
- Model soils as linear elastic (representative for clays at small strains)
- Model the subgrade CBR as 0.5% for this example
- Design Cases:
  - With and without Live Load
  - With and without RailJET

Figure 6-12. Maximum Track Deflection and Long-Term Track Performance.
Sigma/w inputs – No RAILJET™

<table>
<thead>
<tr>
<th>Color</th>
<th>Name</th>
<th>Model</th>
<th>Young's Modulus (E) (psi)</th>
<th>Cohesion (psf)</th>
<th>Unit Weight (pcf)</th>
<th>Poisson's Ratio</th>
<th>Phi (%)</th>
<th>Dilation Angle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast/Subballast</td>
<td>Linear Elastic (Total)</td>
<td>3,000,000</td>
<td>110</td>
<td></td>
<td></td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow CBR = 0.5 Subgrade</td>
<td>Elastic-Plastic (Total)</td>
<td>235,615</td>
<td>150</td>
<td></td>
<td>120</td>
<td>0.45</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Green Concrete Ties</td>
<td>Linear Elastic (Total)</td>
<td>5.1912e+08</td>
<td>150</td>
<td></td>
<td></td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gray Rail</td>
<td>Linear Elastic (Total)</td>
<td>4.176e+09</td>
<td>495</td>
<td></td>
<td></td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diagram showing 40 kip wheel loads on a cross-section with elevation and offset measurements.
Sigma/w inputs – with RAILJET™

<table>
<thead>
<tr>
<th>Color</th>
<th>Name</th>
<th>Model</th>
<th>Young's Modulus (E) (psi)</th>
<th>Cohesion (psf)</th>
<th>Unit Weight (pcf)</th>
<th>Poisson's Ratio</th>
<th>Phi ('')</th>
<th>Dilation Angle ('')</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ballast/Subballast</td>
<td>Linear Elastic (Total)</td>
<td>3,000,000</td>
<td></td>
<td>110</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CBR = 0.5 Subgrade</td>
<td>Elastic-Plastic (Total)</td>
<td>235,615</td>
<td>150</td>
<td>120</td>
<td>0.45</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Concrete Ties</td>
<td>Linear Elastic (Total)</td>
<td>5.1912e+08</td>
<td></td>
<td>150</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>Linear Elastic (Total)</td>
<td>4.175e+09</td>
<td></td>
<td>496</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RailJET Columns</td>
<td>Linear Elastic (Total)</td>
<td>2.500,000</td>
<td></td>
<td>120</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Y-stress Existing Condition

Offset (ft.)

40 kip Wheel Loads

CBR = 2
Y-stress with RAILJET™
XY - Deflection Existing
XY-Deflection with RAILJET™
Top of tie deflection – concrete ties

Vertical Deflection Across Top Tie

- After RailJET with LL, Max = 0.19”
- Existing Condition with LL, Max = 0.33”

Y-Displacement (ft) vs. X (ft)
Long-term life cycle analyses

• KENTRACK Key Assumptions:

• Rail
  • Rail Type – RE 136
  • Rail Section Modulus – 23.56 in
  • Rail Young’s Modulus – 30,000,000 psf
  • Rail Moment of Inertia – 94.9 in^4
  • Rail Tie Spring Constant – 7,000,000 lb/in

• Ties
  • Wood – 7” x 9” x 108”; 20” c-c spacing
  • Concrete - 7” x 9” x 108”; 25” c-c spacing
Damage Analysis – Wood ties

Wood Tie Track - CBR 2%

Damage analyses completed using computer program KENTRACK 4.0. Heavy Traffic Assumed.
Damage analysis – concrete ties

Concrete Tie Track - CBR 2%

- Heavy Traffic
- Medium High Traffic
- Medium Light Traffic
- Light Traffic

Subgrade Design Life (years)

Improved Subgrade Modulus (ksi)

Damage analyses completed using computer program KENTRACK 4.0. Heavy Traffic Assumed.
## Target treatment stiffness – wood ties

Note: estimated composite subgrade modulus values presented here utilize the area replacement ratio methodology that has typically been used for other applications like stone columns. For this assessment, it was assumed that the column stiffness is 20 times stiffer than the surrounding soil.

### Table: Composite Subgrade Modulus Values

<table>
<thead>
<tr>
<th>Case</th>
<th># Columns</th>
<th>Tie Frequency</th>
<th>Soil Type 1</th>
<th>Soil Type 2</th>
<th>Soil Type 3</th>
<th>Soil Type 4</th>
<th>Soil Type 5</th>
<th>Soil Type 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>22,153</td>
<td>37,557</td>
<td>37,326</td>
<td>25,646</td>
<td>25,646</td>
<td>21,511</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>11,895</td>
<td>20,431</td>
<td>20,649</td>
<td><strong>15,534</strong></td>
<td><strong>16,394</strong></td>
<td><strong>16,320</strong></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td><strong>8,475</strong></td>
<td><strong>14,722</strong></td>
<td><strong>15,091</strong></td>
<td>12,163</td>
<td>13,310</td>
<td>14,590</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
<td>31,319</td>
<td>62,701</td>
<td>70,678</td>
<td>94,284</td>
<td>44,149</td>
<td>140,343</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
<td>22,153</td>
<td>37,557</td>
<td>37,326</td>
<td>25,646</td>
<td>25,646</td>
<td>21,511</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td><strong>15,314</strong></td>
<td>26,139</td>
<td>26,208</td>
<td>18,905</td>
<td>19,478</td>
<td>88,024</td>
</tr>
</tbody>
</table>

**20 year subgrade design life**
Target treatment stiffness – concrete ties

<table>
<thead>
<tr>
<th>Case</th>
<th># Columns</th>
<th>Tie Frequency</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>22,153</td>
<td>37,557</td>
<td>37,326</td>
<td>25,646</td>
<td>25,646</td>
<td>21,511</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>11,895</td>
<td>20,431</td>
<td>20,649</td>
<td>15,534</td>
<td>16,394</td>
<td>16,320</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>8,475</td>
<td>14,722</td>
<td>15,091</td>
<td>12,163</td>
<td>13,310</td>
<td>14,590</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
<td>31,319</td>
<td>62,701</td>
<td>70,678</td>
<td>94,284</td>
<td>44,149</td>
<td>140,343</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>2</td>
<td>22,153</td>
<td>37,557</td>
<td>37,326</td>
<td>25,646</td>
<td>25,646</td>
<td>21,511</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>15,314</td>
<td>26,139</td>
<td>26,208</td>
<td>18,905</td>
<td>19,478</td>
<td>88,024</td>
</tr>
</tbody>
</table>

20 year subgrade design life

Note: estimated composite subgrade modulus values presented here utilize the area replacement ratio methodology that has typically been used for other applications like stone columns. For this assessment, it was assumed that the column stiffness is 20 times stiffer than the surrounding soil.
Case 1 – Settlement mitigation over soft subgrade

• Tangent Track
• Existing Subgrade CBR ~ 2%
• Proposed Treatment:
  • Number RailJET Columns = 2
  • Injection Depth = 15 feet
  • Injection Frequency = Every 3rd Tie
Case 2 – Bearing failure over marsh

- **Tangent Track**
- **Existing Subgrade CBR** = 0.5 to 1%
- **Proposed Treatment:**
  - Number RailJET Columns = 2
  - Injection Depth = 30 feet
  - Injection Frequency = Every 2\textsuperscript{nd} Tie
Estimated settlement profile

Estimated Immediate Settlement (No Ground Improvement)

Estimated Immediate Settlement (RailJet)
Case 3 - Shallow slope stability issue

- Curved Track (Experiencing geometry problems)
- Existing Subgrade CBR = 2
- Proposed Treatment:
  - Number RailJET Columns = 4
  - Injection Depth = 25 feet
  - Injection Frequency = Every Tie
No live load – marginally stable
Shallow slope stability issue with Live Load