Effects of Heavy Axle Loads on Track Substructure

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Summary: This paper presents a methodology that was developed to predict the effects of increased axle loading on the track substructure. The method is based on models for calculating the track substructure settlement under repeated axle loading. Examples are given to illustrate the effects of Heavy Axle Load (HAL) traffic on various substructure conditions. These examples will show the deficiencies of the AREMA method for determining the required granular layer thickness. The paper concludes with a brief discussion of alternative remedial techniques to mitigate the effects of the HAL on the substructure.

Index Terms: Ballast, subgrade, substructure, repeated load

INTRODUCTION

The track substructure is comprised of a granular layer consisting of ballast and subballast, and a subgrade that can consist of placed fill material or natural soil as depicted in Figure 1.

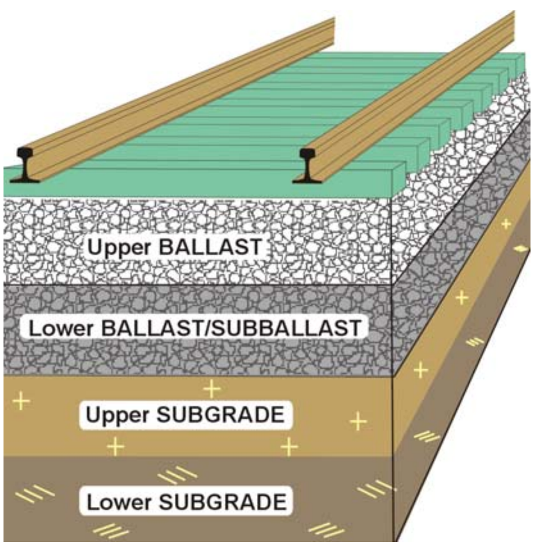

Figure 1: Idealized track substructure.

The top layer represents the ballast that surrounds the ties to hold the track in place. The upper ballast is disturbed periodically by maintenance such as tamping and undercutting/cleaning. The second layer is a combination of lower ballast and subballast that are not disturbed by maintenance. The repeated train loading compacts these layers to the point where they contribute little to the track settlement. These two materials are different and have different functions [3], but they are combined to simplify the model for this paper. The upper subgrade is assumed to be a compressible material under repeated wheel loading. The lower subgrade is assumed to be stiff enough or deep enough that it does not contribute significantly to the track settlement.

The deformation of the track substructure under train traffic is dependent on both the magnitude and the number of repetitions of load, as well as the condition of the granular and subgrade layers. The settlement characteristics of the granular layer (ballast and subballast) are governed by such things as gradation, fouling condition, and water content. The deformation of the subgrade is a function of the strength and stiffness properties of the subgrade soil which are dependent on such things soil type, water content, plasticity, degree of compaction, and loading history.

Railway track substructure layers under high tonnage lines are subjected to millions of load cycles at the same location. The subgrade performance becomes increasingly critical as axle loads increase as well as the number of repetitions of these loads. The design of the substructure is a progressive settlement problem rather than a bearing capacity problem. Track that has been historically stable may begin to deteriorate rapidly after the onset of HAL traffic.

This paper describes a method developed to correctly model the substructure deformation under a mix of traffic loads. Examples will then be presented to show the effects of the HAL traffic on track substructure settlement.

SETTLEMENT DETERMINATION

The track settlement is a result of the compression of the substructure layers under repeated wheel load. Figure 2 shows the stress-strain behavior of the track substructure layers, showing the resilient modulus which represent the stiffness of materials, and the accumulative plastic strain under repeated loading.

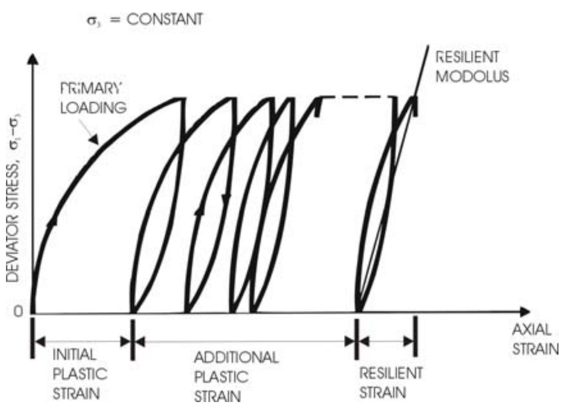

Figure 2: Cumulative Strain and Stiffness of Materials Under Repeated Loading

A model was developed for calculating the cumulative track settlement for any mix of traffic. The model first expresses train traffic in the form of equivalent number of load cycles. The model can represent any mix of traffic (different wheel loads and number of repetitions). This is done by converting the number of cycles of each different wheel load into an equivalent number of cycles of a selected single design load [3, 4].

The model can take into account different layer thicknesses and materials, seasonal variations in the water content, and characteristics of the track superstructure (rails, ties and fasteners). The total settlement of the track under various mixes of traffic is equal to the sum of the compression of the individual layers. For the examples in this paper only the upper ballast and upper subballast were assumed to contribute significantly to the track settlement.

The deformations of the ballast and subballast layers are estimated by methods established by Chrismer and Selig [3,4]. These methods reflect the highly non-linear relationship between granular layer strain and number of load cycles, as shown in Figure 3.

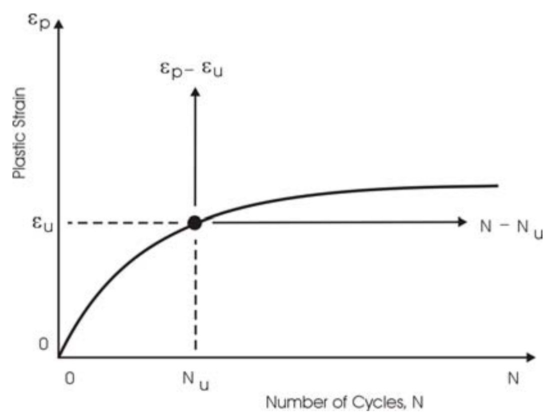

Figure 3: Stress-strain characteristic of soil subjected to repeated loading.

The cumulative strain (compression) increases with increasing numbers of load cycles at a diminishing rate. Conceptually for new construction or newly placed layers the compression begins at zero number of cycles. For existing track the strain begins at cycles $N_{u.}$ This results in a smaller contribution to further load cycles by the layers previously compacted by traffic.

The subgrade settlement was determined using techniques developed by Li and Selig [5, 6]. This method is based on establishing the relationship between layer compression and the traffic characteristics, ballast and subballast properties, and subgrade type.

The analysis technique considers traffic characteristics, ballast and subballast layer thicknesses and properties, and subgrade type and properties. This information is used to calculate strain in the subgrade layers. Given the granular layer and subgrade type, thickness and condition, the settlement of the track is determined.

The stresses in the track substructure were calculated using the GEOTRACK computer program [2]. GEOTRACK is a three-dimensional, multi-layer model for determining the elastic response of the track structure, using stress-dependent properties for the ballast, subballast, and subgrade [7].

EXAMPLES

A series of example cases was developed using the model to illustrate the effects of HAL traffic and track substructure properties on track settlement. The substructure conditions considered are:

1) Poor, fair and good subgrade,

2) Fouling condition of the ballast layer, and

3) Total thickness for the granular layer (ballast + subballast).

Table 1 lists the combinations of traffic that were used in the examples. Traffic is represented by car loading and annual MGT. Cars with 263-kip wheel loads were used to represent standard freight traffic, 315-kip wheel loads were used for HAL traffic, and 133-kip wheel load cars were used to represent passenger train traffic.

Table 1: Traffic Mix Characteristics

Mix	Annual Traffic Mix (MGT)			Traffic (MGT)
	263k cars	315k cars	133k Cars	
1	50	0	0	50
2	40	10	0	50
3	0	50	0	50
4	50	0	10	60
5	0	10	50	60
6	0	0	50	50

Mix 1 represents the nominal case of only standard freight traffic. Mix 2 represents 80% standard freight traffic and 20% HAL traffic, and Mix 3 is only HAL traffic. Mixes 4, 5 and 6 represent various combinations of passenger traffic with either the standard or HAL freight traffic. Mixes 4, 5 and 6 were used in the first example below to illustrate the effects of combining light loads with heavy loads on settlement for various subgrade conditions.

Example 1

The settlements are compared in Example 1 for poor, fair and good subgrade conditions under various mixes of traffic. The deformation and strength characteristics for the three subgrade conditions are given in Table 2. The results of the settlement analysis are presented in Table 3.

Table 2: Properties of Subgrade Soils

Subgrade Condition	Resilient Modulus, E_R (psi)	Compressive Strength (psi)
Poor	1000	4
Fair	2000	8
Good	8000	16

Table 3: Example 1 Results

Mix	Total Settlement (in.) for Subgrade Condition of:		
	Poor	Fair	Good
1	5.3	1.7	0.6
2	6.1	2.0	0.7
3	7.4	2.4	0.8
4	5.3	1.7	0.6
5	6.4	2.1	0.8
6	1.8	0.6	0.2

The nominal case (mix 1) shown in Table 3 is for 50 MGT of standard freight traffic (263-kip cars) with 33-kip wheel loads. For this mix the deformation increases from 0.6 to 5.3 inches as the subgrade changes from good to poor. With the addition of 20 % HAL traffic to the standard freight traffic (mix 2) settlement increases by 15%-20% for all subgrade conditions. This occurs even though the total annual traffic remains at 50 MGT. Going from the standard freight traffic (mix 1) to only the HAL traffic (mix 3) results in at least a 40% increase in track substructure settlement.

The addition of 10 MGT of the light wheel load passenger traffic to the 50 MGT standard freight traffic (mix 4) caused negligible increase in settlement (compared to mix 1). This result illustrates that the substructure deformation is driven by the heaviest load it experiences. The results in Table 3 for mixes 5 and 6 illustrate this even more dramatically. Mix 6 represents all relatively light passenger traffic resulting in a small amount of substructure deformation. Adding only 10 MGT of HAL traffic (mix 5) results in a 2.5 to 4.0 times greater substructure related track settlement.

Example 2

The track settlement was compared for mixes 1 through 3 for clean ballast and fouled ballast conditions. The clean ballast was modeled with a resilient modulus (stiffness) of 45,000 psi, and the fouled ballast was modeled with a modulus of 11,000 psi. These results are based on "fair" subgrade conditions. Table 4 gives the results.

Table 4: Example 2 Results

	Total Settlement (in.) for Upper Ballast Condition of:	
Mix	Clean	Fouled
1	1.7	2.0
2	2.0	2.4
3	2.4	2.8

Table 4 shows that the fouled ballast condition results in 15% to 20% increase in settlement for all three traffic mixes. The impact of HAL on substructure settlement is similar for fouled and clean ballast condition. Changing from Mix 1 to Mix 2 results in approximately 15% increase in settlement for both clean and fouled ballast condition. Changing from Mix 1 to Mix 3 traffic results in a 40% increase in settlement for both clean and fouled ballast.

Example 3

The effect of the thickness of the granular layer on the overall settlement of the track substructure (granular layer and subgrade settlement) is shown in Example 3. "Fair" subgrade conditions were assumed. The results are given in Table 5. Adding a relatively small amount of HAL traffic (10 MGT) to standard freight traffic (Mix 2) results in an approximate 15% increase in track substructure settlement over Mix 1 for all 3 granular layer thicknesses. Increasing from 50 MGT of all standard freight traffic (Mix 1) to 50 MGT of all HAL traffic (Mix 3) results in 35% to 40% increase in settlement for all thickness of granular layer.

Table 5: Example 3 Results

	Total Settlement (in.) for G.L[1] Thickness of:		
Mix	8 in.	18 in.	28 in.
1	1.9	1.7	1.4
2	2.1	2.0	1.6
3	2.6	2.4	1.5

[1] G.L. = Granular Layer

Example 4

AREMA [1] engineering manual recommends a method for determining ballast depth to limit wheel load induced stress on top of subgrade so that the subgrade will not fail. The method involves determining the depth for a given track modulus and wheel load that results in an allowable pressure of 25 psi. This value applies to all soils. The number of load repetitions (amount of MGT) is not considered in the AREMA method.

Example 4 gives results from the method in this paper for comparison with the AREMA method. The parameter R_s represents the ratio of applied stress in the center of the compressible subgrade soil layer (σ_d) to the strength of the subgrade soil (σ_s). Values greater than 1 indicate failure which will cause rapidly increasing settlement with further traffic. As the Rs decreases below failure the settlement decreases. The acceptable settlement dictates how low the cumulative settlement must be. The vertical stress at the top of ballast (directly under the tie) and at the top of subgrade are given in Table 6. The stresses are calculated using GEOTRACK [2] with a HAL wheel load of 39 kip. Finally, the total settlement is given.

According to Table 6, the stress at the top of ballast directly beneath the tie is the highest. It decreases significantly to the value at the top of subgrade. For all cases the stress at the top of subgrade is much lower than 25 psi (i.e., the allowable pressure quoted in AREMA manual), even with a granular layer thickness of only 8 in., and even with the poor soil in a failure state (R_s >1). The correct allowable stress at top of subgrade is not constant, but depends on the soil conditions and number of wheel load repetitions.

The allowable pressure on subgrade from train loading is given in AREMA for purposes of determining required thickness of ballast plus subballast (granular layer thickness) to prevent subgrade failure. Given the allowable pressure and track model the granular layer thickness is governed by the wheel load. According to AREMA manual the allowable pressure to be used for good subgrade is 25 psi. A lower value (no number given) is recommended for poor subgrade. This is inadequate. The allowable pressure varies widely depending on such factors as soil type, water content, and degree of compaction. In addition the allowable pressures decrease with increase in the number of repetitions of load, even for same soil condition.

Table 6: Example 4 results.

		R_s (σ_d/σ_s)	Ballast σ_v (psi)	Subgrade σ_v (psi)	Total Settlement (in.)
Subgrade Condition (w/ 18in. G.L Thick.)	Poor	1.5	65	10	7.4
	Fair	0.8	50	10	2.4
	Good	0.4	40	12	0.8
Granular Layer Thickness (w/ Fair subgrade)	8 in.	0.9	64	13	2.6
	28 in.	0.8	35	9	1.9

REMEDIAL ALTERNATIVE

Some alternatives are available to reduce the settlement in cases where the subgrade is overstressed. Reducing the wheel load and annual MGT are assumed to be unacceptable alternatives in most cases. Two general categories may be designated: 1) with the track in place, and 2) with the track removed (this would include new construction).

Track in Place

With the track remaining in place there are several options for improving the subgrade performance:

1. Improve drainage
2. Increase the granular layer thickness
3. Add tensile reinforcement in the subballast (such as geogrid, geoweb)
4. Use special on-track machines that can renew substructure conditions while working beneath the track.

Track Removed

With the track removed or not yet placed additional options become available:

1. Install proper drainage
2. Remove soft soils and replace with compacted suitable soils
3. Place impermeable membrane to prevent water from coming into contact with the soil
4. Lime or cement stabilization of soils by mechanical mixing
5. Insert hot mix asphalt concrete layer on subgrade

Clearly, designing and installing the substructure to meet the track needs without the track in place is easier and more effective. Obviously many reasons exist why this is not done.

CONCLUSIONS

1. The allowable stress on the top of subgrade for good track performance is determined by cumulative deformation (settlement) rather than by bearing capacity.
2. For a mix of traffic the deformation is mainly caused by the heaviest loads.
3. For the range of wheel loads, number of load repetitions, and soil conditions analyzed in this paper the cumulative settlement ranged from 0.2 to 7.4 in.

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