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Ballast and Subgrade Requirements Study

Office of Research and
Development
Washington, DC 20590

Summary and Assessment Report

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16. Abstract

Earth materials - i.e. soil and rock - form the substructure of all railroad track. In this report a summary and assessment is presented with respect to current and available practices for substructure (ballast, subballast, and subgrade) materials evaluation and selection, stabilization, design and analysis, and performance evaluation. More detailed discussions of this information are presented in the previous two reports of this study entitled "Ballast and Subgrade Requirements Study: Railroad Track Substructure - Materials Evaluation and Stabilization Practices" and "...Railroad Track Substructure - Design and Performance Evaluation Practices." Recommendations for future research requirements for the track substructure are also presented herein.

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Railroad track, Ballast, Subgrade, Subballast, Substructure, Design, Analysis, Performance and Evaluation, Field Tests, Laboratory tests, Ballast and Subballast Evaluation and Selection

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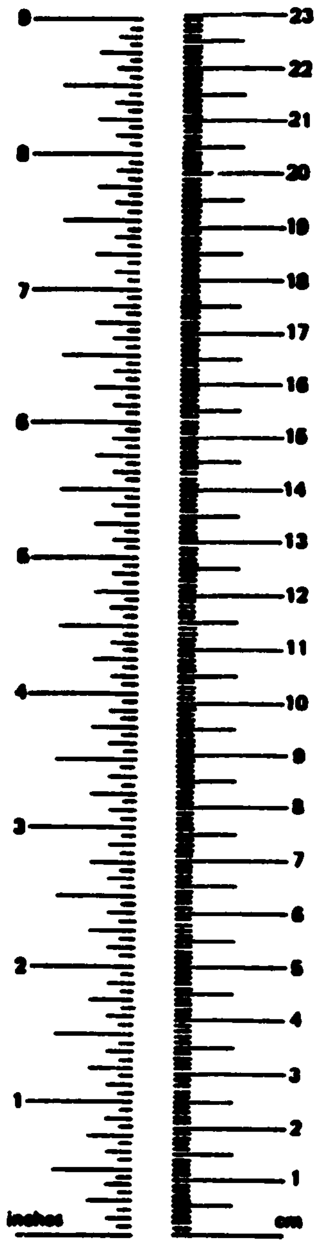
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

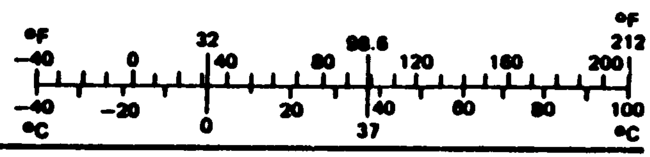
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286, Units of Weight and Measures. Price $2.25 SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This work is part of a study of railroad ballast and subgrade requirements, including synthesis of track substructure materials, engineering and stabilization practices, and practices for the design of the substructure for conventional railroad tracks. This report presents a summary and assessment of information included in the two previous reports of this study. The study was conducted by Goldberg-Zoino & Associates, Inc. (GZA), of Newton Upper Falls, Massachusetts, for the U.S. Department of Transportation's Transportation Systems Center (TSC) in Cambridge, Massachusetts, under Contract DOT-TSC-1527, and was sponsored by the Federal Railroad Administration (FRA), Office of Rail Safety Research, Improved Track Structures Research Division, Washington, D.C.

The TSC Technical Monitor for this project is Mr. James Lamond. Mr. Andrew Sluz of TSC also provided substantial technical guidance during the study. The Principal Investigator for the study was Dr. Richard M. Simon, Senior Geotechnical Engineer at GZA. Dr. Lewis Edgers of the Civil Engineering Department, Tufts University, contributed to the material on subgrade soils and reviewed the report. Mr. James V. Errico of GZA headed the study of subballast. Messrs. Peter K. Kadley and M. Daniel Gordon contributed to the section on substructure stabilization methods. Mr. Lionel Peckover, Geotechnical Consultant, of Quebec, Canada, Mr. J.B. Farris of the Southern Railway, and Mr. K.F. Briggs of the Boston and Maine Railroad provided valuable consulting input on ballast and geotechnical engineering practices of operating railroads. Mr. Mathew A. DiPilato, GZA, was the principal author of the report on design and performance evaluation practices. Mr. Elliot I. Steinberg, GZA, headed the study of lateral and longitudinal loads. Mr. Alyn V. Levergood from the firm of Thomas K. Dyer, Inc. (TKD) of Lexington, Massachusetts contributed to the material on track geometry, design, drainage, and substructure evaluation methods. Messrs. Thomas K. Dyer, Raymond F. Sweeney and Russel W. Maccabe of TKD cooperated with us in development of this report. Mr. Donald T. Goldberg, GZA, contributed significantly to the chapter on subgrade soils and served as overall project reviewer. Ms. Donna Meeker conducted an initial survey of the literature. Ms. Susan Regenbogen Rosinoff was the project's Technical Editor. Ms. Donna Comeau prepared the final typed documents.

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EXECUTIVE SUMMARY

Objective: The objective of this study is to review and synthesize the best available technology that might be applied to design, construction, maintenance, and upgrading of conventional railroad track substructures. The first phase of the study developed suggested practices for exploring, testing, classifying, and selecting earth materials for use in railroad track substructures--i.e., ballast, subballast, and subgrades. The second phase identified available technologies for stabilizing and improving the performance level of track subgrade soils, whether to meet present loading demands with lowered maintenance requirements or to upgrade track to meet demands of higher axle loads or more stringent operating criteria. The final phase surveyed available methods for analysis, design, and performance evaluation of track substructures.

Scope of Study: The scope of this study has been to review available technology in the railroad engineering field, as well as technologies in highway and airfield pavement engineering, geology, foundation engineering, and related areas that can be directly applied to railroad substructure engineering. This review has included a broad survey of published literature, personal communications with practicing railroad engineers and researchers, and our own general expertise in dealing with earth materials in civil engineering construction and railroad maintenance-of-way engineering. In the development of suggested practices for dealing with earth materials, emphasis has been placed on easily performed, repeatable tests that can be economically carried out. Engineering property measurements are recommended where the parameters can be used reliably in analysis or engineering evaluation. Complex testing, such as cyclic triaxial testing of soils and ballast, has been deemphasized because it is believed that the cost of testing is not justified by the variability in results obtained and the natural variability of earth materials themselves.

The review of substructure stabilization included methods to treat subgrade soils to upgrade the performance characteristics of existing track in order to reduce maintenance requirements and to upgrade substructure performance to handle higher axle loads and greater traffic frequency and speed. Subgrade stabilization methods may be implemented for new construction, track rehabilitation, or as a part of regular track maintenance. Emphasis has been placed on those methods that offer the potential for improved substructure performance while requiring limited disruption of the track and train operations.

The design and evaluation procedures that are emphasized herein were selected primarily because they incorporate significant factors related to track design, and because the methods can be easily applied and have been successfully used in practice. In compiling potential performance evaluation parameters and methods, emphasis was placed on those parameters and methods that can provide data on an extensive length of track relatively quickly.

Research Justification: Many American railroads have been beset by financial difficulties. A major factor compounding the financial problems of many railroads is the escalating cost of maintenance. As costs and need for maintenance increase, it has been difficult to expand the maintenance funds to match the need, leading to accelerated deterioration of the track structure. In the railroad industry generally, a deficit of maintenance performed compared to maintenance needed but not performed is increasing, such as for freight service and coal hauling. There is a trend toward higher axle loads that demand greater track strength and stability. There is the need to optimize the application of maintenance funds to counter the trend of increased costs, tighter maintenance budgets, and a demand for track safety and operating efficiency.

To meet the goal of optimizing maintenance expenditures, this study has developed suggested practices for exploring, testing, classifying, and selecting earth materials for use in track substructure. Subgrade stabilization procedures described may be used to upgrade subgrade performance and to reduce maintenance requirements. The best available stabilization technologies are identified, and guidelines are provided for their application to railroad substructure improvement. Another major factor contributing to increased track deterioration has been an increase in wheel loads over those the track structure was designed to handle. While superstructure components such as rails, ties, and fasteners have been upgraded to handle the higher stresses generated by these loads, little has been done to upgrade the track substructure--the ballast, subballast, and subgrade. One reason has been the lack of analytical or design methods available to evaluate the layer thicknesses and material properties required. This study has collected the design methods available to perform these functions, along with new methods being developed.

Summary of Results: Subgrade soils are the natural earth materials that form the base of the track substructure. Since the subgrade is determined by the location of the track route, the first step in subgrade engineering is to explore the subsurface to determine the nature of the subgrade materials. Subsurface exploration is typically done by test borings and test pits or trench excavations. These direct exploration methods may be supplemented by geophysical techniques, such as seismic refraction or electrical resistivity surveys, that can be used to determine the depth of soft soils, the position of the water table, and the top of rock or other stiff layer.

To evaluate the properties of subgrade soils, laboratory engineering property tests, laboratory index tests, and in-situ or field tests may be used. Of the multitude of tests available, the following are judged to be of greatest value for railroad substructure engineering:

a. Laboratory index tests

1. Visual manual soil description
2. Percentage finer than No. 200 sieve

3. Grain size analysis
4. Moisture content
5. Atterberg limits
6. Unconfined or unconsolidated-undrained triaxial shear strength

b. Field tests

1. Standard penetration test
2. Static (Dutch) cone penetration test
3. Field vane shear test
4. Plate bearing test

c. Laboratory engineering tests (as required on a site-specific basis)

1. Consolidation test
2. Consolidation-drained or -undrained triaxial test

In order to transfer substructure engineering practice from one locale to another, it is necessary to describe the subgrade soil properties in an unambiguous way. The Unified Soil Classification system is suggested for classifying subgrade soils.

Ballast performance has received a great deal of attention in the past 10 years. Studies have been carried out using various types of laboratory static and cyclic shear devices. Some full-scale track model tests have studied the effects of cyclic loading on ballast breakdown. A few programs have included systematic evaluation of ballast performance in service track. Generally, these studies have concentrated on the mechanical performance of ballast. Only limited study of environmental, permeability, and maintenance performance was discovered. The mechanical studies have pointed out the significance of particle hardness, toughness, shape, and angularity on the strenth and stiffness of ballast. Confining stress level and shear stress level are also important factors determining resilient and residual stress-strain behavior of the ballast.

Environmental factors have received some attention in the study of pavement aggregates but only limited attention in the railroad field. Freeze-thaw and general chemical mineral alteration are the principal factors that affect ballast performance. The permeability characteristic of ballast of primary significance relates to the movement of fine particles through the ballast bed. This factor is determined by ballast gradation. A broader particle gradation range (less uniform size) might improve ballast resistance to mud pumping from below and fouling of ballast from fines dropped on the surface. However, this hypothesis has had insufficient testing in track to determine its validity. Further study of optimum ballast gradation is warranted.

A great number of laboratory tests may provide indices of potential ballast performance in track. Thirteen have been selected in this study and are suggested as the appropriate tests for selecting and evaluating potential ballast sources. These tests are petrographic analysis, bulk specific gravity and water absorption, grain specific gravity, Los Angeles and mill abrasion tests, point load compressive strength, magnesium sulphate soundness, reference density, flakiness and elongation indices, sieve analysis, static crushing value, and the cementing value test. Definitive limits of parameter values for acceptable ballast have not been established for all these tests. However, if the test parameters are determined for ballasts that are observed to perform both well and poorly in track, it is anticipated that a reliable ballast testing/selection procedure can be developed in the future.

Subballast - The principal function of subballast is to separate the ballast and subgrade while distributing train loads. The subballast may also serve to limit infiltration of surface water into the subgrade. These functions are influenced principally by particle size gradation characteristics. Subballast should have a small amount of fines (material finer than the No. 200 sieve, 2 to 10 percent by weight) and should have a gradation related to the particle sizes of both the ballast and subgrade. Suggested gradation criteria, similar to the criteria developed for graded aggregate filters, are presented in the report.

Substructure Stabilization - refers to measures that treat subgrade soils to improve their performance characteristics. These measures may be applied to new construction or track rehabilitation, or to treat the substructure of in-service track.

Excess water aggravates all types of subgrade soil problems. Improving drainage measures is often the most cost-effective method of substructure stabilization. Drainage is of particular importance for track in cuts and in flat topography. Drainage problems can even develop in substructure of elevated track due to settlements and to development of ballast pockets that destroy the proper grading profile of the subgrade surface.

The most common type of drain used in railroads is the lateral open ditch drain. This is used to carry surface runoff, and if deep enough, to control groundwater level. Interceptor drains, either open or as buried pipe or French drains, are important in controlling water flow in slopes. The principal difficulty in buried drains is preventing movement of fine soil particles. This can be accomplished by providing a filter of properly graded aggregate or plastic filter fabric.

Some methods are available to stabilize subgrade soils in-place. Grouting with sand and/or Portland cement slurries have been used to stabilize slides in railroad embankments and to halt the progress of ballast pockets. the principal benefit is to limit the access of water to the soil.

Lime slurry pressure injection (LSPI) has been tried in recent years to stabilize soft clay subgrades. The lime slurry is injected through pipes that are inserted through the ballast, in order to reduce clay plasticity by means of the chemical reaction with the lime. It is difficult to imagine, however, that sufficient lime can be injected into the soil to achieve significant improvement. Experience indicates that erratic improvement is realized.

Layer inserts have become increasingly popular in track reconstruction to upgrade substructure performance. Subballast is the most commonly used insert and was discussed previously. Filter fabrics or geotextiles have been used increasingly. Fabric provides a means to permit water movement, yet precludes the passage of fine soil particles. Experience with fabrics has seen both success and failure. Application criteria must be developed, such as, (1) do not place fabric directly on pure clay and silt subgrades without a sand blanket, and (2) there must be at least 6 inches, and preferably 8 inches to 12 inches, of ballast between the fabric and the base of the ties.

Many other methods of stabilization are available for railroad applications. These generally require complete disruption of the track and are therefore only applicable to new construction or to complete track rebuild. The primary requirement for successful substructure stabilization is to develop a clear understanding of the mechanisms that are causing substructure displacement. The stabilization methods available to treat the causes of the problem may then be selected with confidence.

Design Practices - The trend in U.S. and Canada has been toward bigger cars and increased wheel loadings, with 100-ton cars rapidly becoming the rule rather than the exception. In the period from 1955 to 1978, the average carrying capacity of cars increased by 43 percent. For the most part, these larger wheel loads are moving over track structures designed for significantly smaller ones.

The wheels apply dynamic loads to the track surface. These dynamic loads occur in two forms: impact loads, such as truck-hunting, nosing, and rock and roll; and vertical bounce and other high frequency vibrations. Impact loads are normally considered in track design by doubling the design static wheel load. The effects of vibrations are poorly understood and generally not accounted for in track design. However, high frequency damping shields, such as hard rubber tie pads, are used to reduce vibration energies transferred through the track structure.

The beam-on-elastic foundation analysis method presented in the American Railway Engineering Association (AREA) Manual for Railway Engineering is the best known analytic method available for U.S. and Canadian railroads today. This method has several limitations in that: 1) it does not adequately represent the performance of individual track components; 2) it evaluates resilient stresses and deformations only; and 3) it does not consider repeated dynamic loading or residual displacements of components. The track modulus, u, is used to represent the stiffness of ties, ballast, subballast, and subgrade. Many factors affect the value of u, but these factors are difficult to isolate. Little attention is paid to determing the type, strength, and conditions of subgrade soils and to incorporating these properties into analysis and design.

The principal criterion for track substructure design today is limiting the pressure on the subgrade to an amount the subgrade can support: AREA recommends a limit of 20 psi. This, however, may lead to performance difficulties in loose fine sands, clays, silts, and dumped uncompacted fills since the allowable bearing pressure of soils varies. In our opinion, this area of track substructure design requires further study.

Several analytical computer models representing the individual track structure components have been developed over the past 10 years. The promise of analytic tools such as these is their ability to model the influence of different track structure conditions economically. They can be used to perform parameter studies to determine the effects of changing load, rail, tie, ballast, subballast, and subgrade properties on the performance of other track components and on the track structure as a whole. Few parameter studies of this nature are available. A method for predicting the residual deformation of the ballast is in the preliminary stages of development and must be extended to predictions of subballast and subgrade deformations. Field data are necessary to validate theoretical deformation predictions. The method predicts uniform total deformations. However, it is differential settlement along the track that is of real interest to railroad engineers. With the accumulation of field settlement data, an emprical means of estimating differential settlement from average settlement could be developed.

Performance Evaluation Practices - Substructure performance criteria should be based on three basic functions of the track substructure: maintaining geometry, providing a resilient support layer, and providing rapid drainage.

The purposes of track observation methods are to (1) identify safety-related track defects, (2) monitor general conditions and changes in track conditions, (3) evaluate maximum service level of a track section, and/or (4) evaluate existing track performance in order to develop a design to upgrade performance.

Visual inspection is the most common observation method used today in the U.S. and Canada; however, it is subjective and based on the experience of the observer. Track geometry cars are becoming more widely used to supply track geometry data. Lateral load tests have been used infrequently to evaluate the lateral load resistance of track. Track modulus tests and various types of plate load tests have been used to measure substructure resilience, along with a dynamic system used on track geometry recorder cars.

No single method can satisfy the different requirements or purposes for substructure evaluation. Several methods are presented, each with its proper application. Further development and experience with these recommended methods are necessary before suggested guidelines for their application can be developed.

1. INTRODUCTION

The Railroad Ballast and Subgrade Requirements Study was carried out to identify those areas of engineering practice and research that can be of direct benefit to the railroad industry for the design and construction of track substructures--i.e. the ballast, subballast, and subgrade--and improvement of track substructure through subgrade stabilization. The objective of the study was to review and synthesize the best available technology that might be applied to design and construction of conventional railroad track substructure. The first phase of the study developed suggested practices for exploring, testing, classifying, and selecting earth materials for use in railroad track substructure. The second phase identified available technologies for stabilizing and improving the performance level of track subgrade soils, either to meet present loading demands with lowered maintenance requirements or to upgrade track to meet demands of higher axle loads or more stringent operating criteria. The results of the first two phases of the project were discussed in the first final report entitled, Railroad Track Substructure - Materials Evaluation and Stabilization Practices. The final phase, covered in the second final report entitled, Railroad Track Substructure - Design and Performance Evaluation Practices, surveyed available methods for analysis, design, and performance evaluation of track substructure.

In this, the final report of the study, the results of each area of the study are summarized. The technology associated with each phase is assessed, and areas that require further development prior to implementation of substructure engineering guidelines are identified. Section 2 discusses practices for earth materials evaluation for track substructure construction. Section 3 describes practices for subgrade stabilization. Section 4 discusses methods for design of track substructures and procedures for evaluation of substructure performance, including the results of the single lateral tie push tests. Section 5 recommends areas of research needed to develop technologies. Conclusions are presented in Section 6.

2. EARTH MATERIALS FOR TRACK SUBSTRUCTURE

In conventional railroad track--in which the rails are fastened to individual crossties--earth materials are used to construct ballast and subballast layers. Together, the ballast, subballast, and subgrade comprise the track's substructure, and the rails, fasteners, and ties comprise the superstructure. All these elements interact to provide a track with a set of performance characteristics that affects the operation of trains.

To provide suitable support and a guideway for train operations, track geometry should be set following specifications that are appropriate for the desired operating speed. Over time, the track is expected to retain this geometry, although it will be subject to stress from train loading and the environment.

The engineering of a railroad track's substructure should be aimed toward providing a substructure that:

a. Readily permits maintenance operations to set the desired initial track geometry, and

b. Limits the track displacements induced by the response of the substructure elements.

The synthesis of available procedures for evaluation of earth materials was based on a review of practices in the fields of railroad maintenance-of-way engineering, highway engineering, foundation engineering, concrete technology, geology, and soil and rock mechanics. Each element of the substructure/ballast, subballast, and the subgrade--performs particular functions and should display properties that suit it to perform its intended functions.

2.1 SUMMARY OF SUBSTRUCTURE MATERIAL PRACTICES

Both the similarities and differences in the properties of the substructure elements have been reviewed as summarized below.

Subgrades

The variability of soils along even a single section of railroad track will exceed the variability of all other components of the track; the properties of the subgrade are generally a function of the route selected. Therefore, track substructure design must accommodate the properties of the existing subgrade. With respect to track subgrades, the recommended practices set forth criteria for exploration, evaluation, and quantification of subgrade soil properties and classification of soils for use in track design and rehabilitation procedures.

Explorations - The following guidelines are recommended for exploration of subgrade soils for substructure engineering:

Cuts - In cut areas, the principal concerns are:

a. Water table location

b. Type of soil to be excavated

c. Stability of cut slopes

d. Volumetric soil expansion (swell)

e. Frost heave potential

f. Nature of soils at cut subgrade

g. Construction problems inherent in working equipment within the excavation.

Guideline recommendations for exploration in cut areas are as follows:

a. For cuts terminating above the water table, provide boring or test pit to 5 feet (1.5m) below proposed subgrade at average 500-foot (150m) spacing.

b. For cuts terminating below the water table, the depth of boring below subgrade elevation should be at least equal to 1.5 times the depth that the excavation subgrade is below the water table. The reason is related to seepage into excavation from underlying pervious strata, especially where artesian conditions may exist. Average distance between borings should be 500 feet (150m).

c. In areas of potential slope instability, provide additional explorations to whatever depth and lateral extent necessary to define conditions behind the slope and below the toe.

d. Borings must penetrate weak strata, expecially weak cohesive soils.

Fills - Principal concerns regarding subgrade below fills are as follows:

a. Settlement due to consolidation of compressible strata

b. Displacement of subgrade by shear failure of weak strata

c. Soft to medium clays are typically the most troublesome.

d. Granular soils usually perform satisfactorily under fill.

Guideline recommendations for exploration in fill areas are as follows:

a. For low fills (less than about 20 feet), space borings about 1,000 feet (300m) apart. Recommended boring depth is at least equal to width of proposed fill or to competent material. Where fill is underlain by unstable soils, such as peat or soft clay, space borings no more than 500 feet (150m) apart. Boring depth should be to competent material.

b. For high fills (more than about 20 feet), space borings about 500 feet (150m) apart. Depth of borings should be at least equal to width of fill or to competent material.

c. Where high fills are constructed over soils deposited by or in water (fluvial, lacustrine, glaciofluvial, etc.), at least half of borings should fully penetrate such deposits, but to depth not more than twice the fill width.

d. In areas of potential embankment instability and/or excessive settlement, provide additional borings to whatever depth and at locations necessary to define conditions. Borings must penetrate weak strata, especially weak cohesive soils.

Performance Characteristics - Although track performance may be considered in terms of displacements, material performance that affects track displacements may be more readily defined in terms of the following material characteristics:

a. Mechanical Characteristics - Related to the ability of soil to support the track structure, ballast, and subballast, and to accommodate superincumbent train loads (both single, repeated, and dynamic) with acceptably small displacements.

b. Environmental Characteristics - Related to the resistance of the subgrade to alteration from temperature, water, or other nonmechanical factors.

c. Permeability Characteristics - Related to the passage of water through the subgrade soils and the penetration of ballast or subballast into the subgrade and vice versa.

d. Construction Characteristics - Related to the sensitivity of the soil to disturbance by construction traffic and the workability of the soil as it is moved or altered (compacted) during construction.

In development of the earth materials practices report,[1] soil behavior was discussed in terms of these characteristics. Included was a brief review of the theoretical principles that are currently used to represent the observed behavior of soils and rocks with respect to the engineering properties of strength, stiffness, and permeability. The report also included a description of common engineering property tests and how test findings are used to derive engineering properties. Although these tests yield parameters of engineering performance that may be used in analysis--in particular, mechanical parameters for predicting displacement--they have several limitations: specifically, the effects of sample disturbance, stress states, and strain rates on test results; and the cost of test equipment and the training of personnel involved in implementing the tests. Due to the costs, a limited number of engineering property tests may have to be carried out along a section of track, and test results must be extrapolated to represent an entire track section. For these reasons, we believe that index property tests should be an important part of any program for studying railroad track subgrades. Index tests are simple, economical laboratory and field tests that provide an indirect measure of soil engineering properties. The results of index tests may be used to help extrapolate the results of engineering property tests.

Subgrade Classification - For railroad engineering the Unified Soil Classification System (USC) is recommended for classification of subgrade soils. Procedures for classifying soils by laboratory tests and by visual-manual methods in the field have been well developed for the USC. In addition, the soil classes have been associated with various ranges of engineering properties, as shown in Table 2-1. In completing soil descriptions, index test parameters should be measured and reported, as outlined in Table 2-2.

Ballast

Ballast is a select material placed under and around the crossties to support the railroad track, distribute train loads, and maintain the superstructure geometry. The major problem associated with ballast is selecting materials that will limit overall track displacements over time. The displacements induced by the ballast layer are determined by the three primary classes of material performance characteristics: mechanical, environmental, and permeability. These performance characteristics determine how the ballast material will respond to train loads and how the mechanical response will change with time due to mechanical and environmental effects.

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[1] R.M. Simon et al., "Railroad Ballast and Subgrade Requirements Study: Railroad Track Substructure - Materials Evaluation and Stabilization Practices," U.S. Department of Transportation, Federal Railroad Administration, Washington DC, 1983, FRA/ORD-83/04.1, 381 p.

TABLE 2-1. UNIFIED CLASSIFICATION SYSTEM SOIL GROUPS: CHARACTERISTICS AND USES

Major Divisions		Letter (1)	Name	Unit Dry Weight Lb per Cu Ft (2)	Field CBR	Subgrade Modulus k Lb per Cu In	Compressibility and Expansion	Potential Frost Action (3)	Drainage Characteristics (4)	Value as Filter Layer (5)	Erosion on Exposed Slope (6)	Value of Subgrade (7)	Pumping Action (8)	Stability in Compacted Fills (9)	Compaction Characteristics (10)
COARSE GRAINED SOILS	GRAVEL AND GRAVELLY SOILS	GW	Well-graded gravels or gravel-sand mixtures, little or no fines	125-140	60-80	300 or more	Almost none	None to very slight	Excellent	Fair	None *	Excellent	None	Very good	Excellent, crawler-type tractor, rubber-tired roller, steel-wheeled roller
		GP	Poorly graded gravels or gravel-sand mixtures, little or no fines	110-130	25-60	300 or more	Almost none	None to very slight	Excellent	Fair to poor	None *	Excellent	None	Reasonably good	Good, crawler-type tractor, rubber-tired roller, steel-wheeled roller
		GM d	Silty gravels, gravel-sand-silt mixtures	130-145	40-80	300 or more	Very slight	Slight to medium	Fair to poor	Very poor	None to slight	Good'	None	Reasonably good	Good with close moisture control, rubber-tired roller, sheepfoot roller
		GM u		120-140	20-40	200 to 300	Slight	Slight to medium	Poor to practically impervious						
		GC	Clayey gravels, gravel-sand-clay mixtures	120-140	20-40	200 to 300	Slight	Slight to medium	Poor to practically impervious	Not to be used	None to slight	Good	Slight	Fair	Excellent, rubber-tired roller, sheepfoot roller
	SAND AND SANDY SOILS	SW	Well-graded sands or gravelly sands, little or no fines	110-130	20-40	200 to 300	Almost none	None to very slight	Excellent	Excellent	Slight to high with decreasing gravel content	Excellent	None	Very good	Excellent, crawler-type tractor, rubber-tired roller
		SP	Poorly graded sands or gravelly sands, little or no fines	100-120	10-25	200 to 300	Almost none	None to very slight	Excellent	Fair to poor	High	Good	None	Reasonably good with flat slopes	Good, crawler-type tractor, rubber-tired roller
		SM d	Silty sands, sand-silt mixture	120-135	20-40	200 to 300	Very slight	Slight to high	Fair to poor	Very poor	High	Poor	None to slight	Fair	Good with close moisture control, rubber-tired roller, sheepfoot roller
		SM u		105-130	10-20	200 to 300	Slight to medium	Slight to high	Poor to practically impervious						
		SC	Clayey sands, sand-clay mixtures	105-130	10-20	200 to 300	Slight to medium	Slight to high	Poor to practically impervious	Not to be used	Slight	Poor	Slight	Fair	Excellent, rubber-tired roller, sheepfoot roller
FINE GRAINED SOILS	SILTS AND CLAYS LL < 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	100-125	5-15	100 to 200	Slight to medium	Medium to very high	Fair to poor	Not to be used	Very high	Poor	Slight to bad	Poor	Poor to good with close control of moisture, rubber-tired roller, sheepfoot roller
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	100-125	5-15	100 to 200	Medium	Medium to high	Practically impervious	Not to be used	None to slight	Bad	Bad	Reasonable	Fair to good, rubber-tired roller, sheepfoot roller
		OL	Organic silts and organic silt-clays of low plasticity	90-105	4-8	100 to 200	Medium to high	Medium to high	Poor	Not to be used	Variable	Bad	Very bad	Not to be used	Poor to very poor
	SILTS AND CLAYS LL > 50	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, plastic silts	80-100	4-8	100 to 200	High	Medium to very high	Fair to poor	Not to be used	None to slight	Bad *	Very bad	Poor	Poor to very poor, sheepfoot roller
		CH	Inorganic clays of high plasticity, fat clays	90-110	3-5	50 to 100	High	Medium	Practically impervious	Not to be used	None	Bad	Very bad	Fair with flat slopes	Fair to poor, sheepfoot roller
		OH	Organic clays of medium to high plasticity, organic silts	80-105	3-5	50 to 100	High	Medium	Practically impervious	Not to be used	Variable	Bad	Very bad	Not to be used	Poor to very poor
HIGHLY ORGANIC SOILS		Pt	Peat and other highly organic soils	—	—	—	Very high	Slight	Fair to poor	Not to be used	Not applicable	Remove completely	Very bad	Not to be used	Compaction not possible

NOTES:

(1) Division of GM and SM groups into subdivisions of d and u are for roads and airfields only; subdivision is on basis of Atterberg limits; suffix d (e.g. GMd) will be used when the liquid limit is 28 or less and the plasticity index is 6 or less; the suffix u will be used when the liquid limit is greater than 28.

(2) Unit dry weights are for compacted soil at optimum moisture content for modified AASHO compactive effort.

(3) These soils are susceptible to frost as indicated under conditions favorable to frost action described in the text.

(4) Ability of soil to drain water by gravity. Drainage ability decreases with decreasing average grain size.

(5) Value of soil as filter backfill around subdrain pipes to prevent clogging with fines, and as filter layer to prevent migrations of fines from below.

(6) Ability of natural soil to resist erosion on an exposed slope. Soils marked * may be used to protect eroding slopes of other materials.

(7) Value as stable subgrade for roadbed, when protected by suitable ballast and subballast material. Good soils may be used to protect poorer soils in subgrade.

(8) Tendency of soil to pump up and foul ballast under traffic.

(9) Stability of soil against bulging and subsidence when used in a rolled fill. Cross-check with column (6) to forecast tendency to erode.

(10) The equipment listed will usually produce the required densities with a reasonable number of passes when moisture conditions and thickness of lift are properly controlled. In some instances, several types of equipment are listed, because variable soil characteristics within a [illegible]

REFERENCES: U.S. Army Corps of Engineers, 1953, "The Unified Soil Classification System", Technical Memo. 3-357, Appendix B, Table B-1.

AREA, (1976) Manual for Railway Engineering, p 1-1-32 33.

TABLE 2-2. RECOMMENDED SUBGRADE SOIL TESTS

1. Visual-Manual Description (D2488)*

2. Material finer than No. 200 Sieve (D1140)

3. Standard Penetration Test (N) (D1586)

4. Groundwater Observation (in boreholes or observation wells)

5. Coarse-Grained Soils
   a. Grain Size Analysis (D422), (C_u, C_c, D_{10})
   b. Burmister and Unified Classifications

6. Fine-Grained Soils
   a. Moisture Content (D2216)
   b. Liquid Limit (D423)
   c. Plastic Limit and Plasticity Index (D424)
   d. Unified Classification (D2487)
   e. Unconfined Compression (D2166) or Triaxial UU (preferred)

7. Tests to be selected in a site specified testing program designed on the basis of above tests or on the basis of local experience. See text.
   a. Static Cone Penetration Test (D3441)
   b. Field Vane Test (D2573)
   c. Plate Bearing Test (D1194)
   d. Percolation Test (D3385)
   e. Shrinkage Factors (D427)
   f. Specific Gravity of Solids (D854)
   g. Organic Content (D2974)
   h. Minerologic Tests (Cation Exchange, X-Ray Diffraction)
   i. Consolidation Test (D2435) (Including measurement of swell pressure or free swell, if appropriate)
   j. Triaxial Consolidated Drained or Undrained Tests
   k. Seismic Refraction

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*Number in brackets indicates ASTM Standard if C or D prefix, or AASHTO Standard if T prefix.

Recent research on the performance of railroad ballast has concentrated on mechanical performance, with researchers often using sophisticated laboratory tests. Triaxial tests are most commonly used, although direct shear, plate loading, and lateral tie push tests have also been evaluated. These studies have led to substantial conclusions concerning the mechanical performance of fresh ballast. However, these studies have provided little insight into the processes that we believe may be even more significant than mechanical performance: i.e., ballast breakdown due to weathering and ballast fouling due to the intrusion of subgrade soils and surface contaminants into the ballast. These factors are determined by the environmental and permeability performance characteristics of the ballast.

Index tests may also be used to estimate ballast performance characteristics. Currently, the AREA Manual for Railway Engineering specifies acceptable limits for several index parameters; however, the limits provided do not preclude the use of all ballasts that perform poorly and may reject some suitable materials. Therefore, it is desirable to consider using a larger group of index tests to qualify potential ballast sources accurately and to compare service ratings of ballast. Table 2-3 lists thirteen index tests that are a suggested guide to classifying ballast accurately and uniformly and to characterizing potential ballast performance. These tests are intended to provide parameters that are indicative of mechanical, environmental, and permeability performance, as well as the response of the ballast to construction and maintenance operations.

Correlations between index test parameters and observed field performance require further verification in the field. Future ballast research should seek to relate ballast performance to practical laboratory and field tests so that railroad ballast sources may be optimally selected and service life predictions may be made; i.e., engineers will be able to anticipate the required ballast maintenance frequency from predictions of ballast-induced track displacements.

Subballast

Subballast performs functions similar to those of the ballast layer, such as supporting the track and train loads. In addition, the subballast layer separates the ballast from the subgrade. This function helps the ballast perform its job by limiting the fouling of ballast due to subgrade intrusion. Likewise, subballast limits the intrusion of ballast into the subgrade. The subballast layer also helps preserve the properties of the subgrade by draining the water that percolates down through the ballast to the sides of the track. This action limits the vertical movement of water through the subballast that might soften subgrade soils.

Subballast materials, i.e., natural sands, gravels, and crushed rock aggregates, must exhibit suitable mechanical, environmental, and permeability performance characteristics to limit track displacements. The level of mechanical and environmental performance characteristics for subballast can be lower than that for top ballast. Of course, the subballast must be able to maintain

TABLE 2-3. RECOMMENDED INDEX TESTS FOR BALLAST COMPACTION

1. Petrographic Analysis [C295]*

a. Hand sample identification of mineral constituents and percentages, geologic rock classification name (e.g., granite, rhyolite, basalt, granodiorite, gneiss, limestone, dolomite), blast furnace slag, and common rock name (e.g., granite, traprock, limestone).

b. Abrasion test fines sample: description of minerals present, description of fines as abraded dust or fractured, angular particles.

c. Polished section or thin section examination if required by petrographer.

d. Subjective evaluation concerning toughness, hardness, secondary alteration, weatherability of fresh minerals, weatherability of fines, variability of source rock properties.

2. Bulk Specific Gravity [C127]

3. Water Absorption [C127] (Degree of Saturation)

4. Grain Specific Gravity (Total Porosity) [International Society for Rock Mechanics, 1972]

5. Los Angeles Abrasion [C535]: Dry (grading to be specified)
Wet (add 50% by weight water)

6. Point Load Compressive Strength [International Society for Rock Mechanics, 1974]

7. Mill Abrasion Test [Raymond, 1979]

8. Sulfate Soundness [magnesium sulfate, 5 cycles, 10 cycles, C88)]

9. Reference Density Test [Selig et al., 1977]

10. Flakiness, Elongation Indices [British Standards Institute, Vol. 812]

11. Sieve Analysis [Gradation Modulus ($\bar{A}$) and Coefficient of Uniformity (C_u)] [C136, Hudson and Waller, 1969]

12. Crushing Value [British Standards Institute, Vol. 812]

13. Cementing Test [ConRail-modified]

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*Indicates ASTM Standard Test Method.

its inherent properties even when subject to train loading and exposed to extremes in weather. Lower strength and stiffness are required for subballast because it is subjected to lower shear stresses than the ballast. The top ballast acts as an insulating blanket, so that subballast is subject to fewer freeze-thaw cycles per annum than ballast. However, the subballast may remain saturated for longer periods.

Permeability is the most important characteristic to consider in selecting a subballast material. Subballast aids in the collection of water that enters the ballast and transfers the water to lateral drainage facilities. Therefore, subballast should have a moderate permeability, high enough to limit buildup of internal pore pressures within the subballast, yet low enough to limit surface water from entering the subgrade through the subballast. Subballast should also prevent mixing with either ballast or subgrade. Hence, the material should satisfy gradation criteria similar to those developed for the piping of soils into graded filters. However, research into the criteria for satisfactory grading to avoid intrusion of ballast and subgrade soils into the subballast is just beginning.

It is also important to consider the behavior of a subballast material during construction before choosing it for a particular project. Construction performance relates to the ease with which the material can be placed into a stable layer with satisfactory mechanical characteristics. Generally, this concerns the compaction characteristics of a material and the sensitivity of material performance characteristics to compaction water content. Subballast should be placed at a high unit weight, at least 100 percent of the maximum standard Proctor dry unit weight.

The materials commonly used and available as subballast are similar to the materials used in highway construction. Therefore, the index test procedures that might be used to characterize subballast are already well established. Recommended index tests for subballast are as follows:

a. Particle-size analysis

b. Moisture density relation (Compaction or Proctor test)

c. Liquid and plastic limits (if cohesive)

d. Los Angeles abrasion resistance.

To perform the separation function, the gradation of subballast should be selected based on particle size criteria similar to those developed for aggregate filters in drainage structures. However, the criteria for subballast probably need not be as stringent as for drainage filters. The following criteria are suggested:

a. $\frac{D_{15} \text{ (subballast)}}{D_{85} \text{ (subgrade)}} < 6 \text{ to } 8$

b. $\frac{D_{50} \text{ (subballast)}}{D_{50} \text{ (subgrade)}} < 25$

c. $C_u = \frac{D_{60} \text{ (subballast)}}{D_{10} \text{ (subballast)}} = 10 \text{ to } 20$

where -

D_n = Sieve size opening through which n percent of the material will pass

C_u = Coefficient of uniformity.

To provide a low permeability to limit vertical percolation of water and to provide a material that is easily compacted and retains stability in service, subballast should contain 2 to 8 percent material by weight finer than the No. 200 sieve (0.075 mm). Low- to nonplastic fines are preferable. Swelling clay minerals must be avoided.

2.2 ASSESSMENT OF EARTH MATERIALS TECHNOLOGY

The technology related to exploring, testing, classifying, and evaluating subgrade soils and subballast is well developed because these materials and procedures have received widespread use in engineering and construction of pavements and in many other types of civil engineering structures. Use of these procedures should be verified for railroad application.

The use of uniformly graded coarse aggregates as ballast with complete exposure to the environment and high dynamic stress levels is restricted to railroad practice. The technology related to ballast materials leaves significant voids to be filled by future development. Those areas of earth material technology requiring further research in order to develop or confirm guidelines for railroad applications are discussed below.

General

One of the most significant shortcomings in dealing with railroad substructures is the dearth of objective, in-service observations of performance and associated details of the substructure system for standard gauge, heavily loaded railroad track as used in North America. Published performance observations and descriptions of the substructure are available for the U.S. Department of Transportation, Facility for Accelerated Service Testing (FAST) Track in Pueblo, Colorado. This elaborate research effort is an important step toward development of an in-service data base. However it represents only one subgrade and environmental condition, one that is generally associated with satisfactory substructure performance.

Another important field performance program was carried out by the Canadian National Railway (CNR) system at a site outside Montreal. This program studied only the performance of various ballast materials[2]. These data formed the basis of statistical correlations between laboratory index properties as commonly used in ballast specifications and subjectively quantified measures of ballast performance[3].

The report on earth material practices[4] sets forth recommendations for laboratory testing and characterization of substructure materials both as candidates for construction and in track. These procedures are suggested for use in conjunction with in-service performance observations to characterize the substructure elements and to provide measures of material performance. Some additional measures of substructure performance require further development as discussed below. Sites covering a wide range of subgrade and environmental conditions must be studied. Further details are provided in Section 5. It is our opinion that this approach to track substructure research will provide the most useful and reliable criteria for substructure material guidelines, as well as data for evaluation of design criteria.

Subgrade Engineering Technology

The procedures available for testing, characterizing, and classifying subgrade soils for railroad substructure engineering have been adequately developed. As discussed previously, the missing link is the relation between subgrade material properties and performance of track substructures in service. Part of this link is related to the problem of evaluating analytic procedures for design of substructures to sustain train loads and choosing substructure material parameters for analysis. These factors will be discussed in Section 4.2. Other factors related to subgrades are discussed below.

Frost - A procedure has been developed by the U.S. Army Corps of Engineers for design of highway and airfield pavements to protect against the effects of both freezing and thawing of soils. Generally the procedure is based

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[2]C. J. Dalton, "Field Durability Tests on Ballast Samples as a Guide to the Significance of the Specification Requirements," Canadian National Railways Technical Research Center, St. Laurent, P.Q., 1973, 40 pp.

[3]P.N. Gaskin and G. P. Raymond, "Contribution to Selection of Railroad Ballast," Transportation Engineering Journal, ASCE, Vol. 102, No. TE2, Proceedings Paper 12134, May 1976, pp. 377-394.

[4]R. M. Simon et al., Op. Cit., pp. 18-75, 75-77.

on (a) evaluating the depth of frost penetration from temperature data and designing a pavement system that limits penetration of frost into damage-susceptible soils, and (b) providing sufficient pavement strength to hold up under load on a thaw-weakened subgrade. The optimum design balances both frost depth protection and bearing resistance for reduced subgrade support. It is clear that an analogous procedure can be developed for railroad practice; however, it will require in-service observations of track performance, temperature data, soil and groundwater data, and observed frost penetration depths to develop the frost design guidelines for railroad track.

Geophysical Explorations - Seismic and electrical resistivity surveys were described in the Materials Evaluation Practices[5] report as the developed geophysical methods most suitable for exploration of railroad subgrades. These methods are used frequently in allied civil engineering applications to define subsurface layering as well as seismic velocity and subsurface electrical properties. As indicated in Table 2-2, these methods may be well suited to specific applications. Other methods have been studied, at least preliminarily, by the U.S. Waterways Experiment Station, including subsurface radar and vibroseismic reflection. The subsurface radar used electromagnetic waves to discover subsurface layering. The method is particularly sensitive to changes in water content in earth materials. Radar may be suitable to explore for the presence and extent of ballast pockets and other substructure conditions in existing track; however, practical limitations have restricted development of this method. The vibroseis uses a large, variable frequency vibrator to determine the resonant condition of the vibrator-substructure system. This method may provide a quick means of providing resilient properties of subgrades or of the entire track substructure. Considering the lineal nature and large extent of railroad track, geophysical exploration techniques would be well suited to exploration of the track substructure. However, further testing, including field application trials, is needed before guidelines for application and interpretation of any technique can be established.

Subgrade Classification - The Unified Soil Classification system is judged to be adequate for classifying subgrade soils. The major limitation is implementation of this uniform system of subgrade description so that experience from different locales can be compared on the basis of similar subgrade engineering performance as represented by subgrade soil group.

Ballast Technology

Considerable research has been carried out in the last ten years into the properties and performance of railroad ballast materials. The bulk of the effort reported in the literature has centered on mechanical laboratory

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[5]R. M. Simon et al., Op. Cit., pp. 57-60.

tests of ballast samples--triaxial, cyclic triaxial, and direct shear tests. This work has had two goals: (1) developing constitutive relations for ballast to be used in analysis of track systems, particularly computer models; and (2) defining the effects on shear strength of such factors as initial density, confining stress, gradation, particle shape, mineralogy, water content, and stress history. As presented in the materials evaluation practices report[6], the results of these studies are generally well understood, at least qualitatively.

Other than the observations at FAST and by the CNR previously referenced, few systematic observations of ballast performance in-service are available. The laboratory test programs have concentrated on mechanical performance with little investigation of response to environmental influences and the effects of construction/maintenance operations. Only the work reported by Gaskin and Raymond (1976) attempted to measure influences of environmental factors in-service.

Factors related to ballast properties for analysis will be discussed in Section 4.2. Assessment of other factors related to ballast are discussed below.

Index tests - A suite of thirteen index tests (Table 2-3) is presented as a means to characterize and classify ballast. Some of these tests have been used for many years to qualify ballast samples; others have never been used for routine ballast testing. Although selection of these particular tests was based on a logical, as well as an empirical, relation between the measured index property and a performance characteristic, the effectiveness of each test, and of the suite of tests, to correlate with individual performance characteristics, as well as overall ballast performance, remains relatively unexplored.

It is judged that in-service observations of ballast performance coupled with the index test results can provide the data on which to base guidelines for ballast material selection and eventually service life predictions. Many factors must be considered simultaneously, including loading, environment, geometry, external fouling, and superstructure, so that the effects of individual factors may be discerned. Laboratory tests alone are not judged to be adequate to provide the necessary data. The laboratory is particularly limited in reproducing weathering effects since weathering is not now fully understood. This understanding will come from field studies. Only coupled field and laboratory studies can explore all significant factors. This approach should prove the most efficient and reliable means to develop ballast selection guidelines.

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[6]R. M. Simon et al., Op. Cit., pp. 82-89.

Subballast Technology

Procedures for selecting and using materials for subballast are well developed, since the materials are frequently the same as those used in pavement structures. Recommended procedures for testing and classification of subballast have been presented previously and in the materials evaluation practices report[7].

The principal uncertainty in selecting subballast materials is in specifying gradation requirements that satisfy the filtering and permeability performance requirements. Recommended criteria have been presented based on comparisons with criteria developed for drainage filters. However, few studies of subballast performance per se have been carried out.

In 1979, G.P. Raymond reported in "Ballast Properties That Affect Ballast Performance," on a preliminary laboratory test program to study the layer mixing phenomenon of subballast and subgrade soil. The test involved a cyclically loaded footing bearing on a layer of subballast over compacted subgrade soil. Intrusion of subgrade into the aggregate was observed after several thousand load cycles. Raymond did not report results at that time. The laboratory test program is judged to be an important preliminary study to refine the gradation criteria as proposed herein. The study may include two-layer subballast systems, such as a sand blanket below sand and gravel, as well as filter fabric in association with aggregates. However, any conclusions based on the laboratory study should be considered preliminary until verified by field observations. A test section, similar to the CNR ballast test section, should include several subballast gradations and other protective blankets.

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[7] R. M. Simon et al., Op. Cit., pp. 126-135.

3. SUBGRADE STABILIZATION

Subgrade stabilization is the treatment of track subgrade conditions to improve performance characteristics. Stabilization may be carried out in preparation for new construction, in association with track rehabilitation, or in conjunction with routine maintenance. The intent of subgrade stabilization is to reduce the requirement for extra ballast and subballast thickness, to reduce maintenance frequency and cost, and/or to upgrade or maintain track performance to meet increased loading magnitude or frequency. The principal need in railroad engineering is for effective stabilization methods that may be applied without disrupting track operations.

Subgrade problems or deficiencies may be divided into two general classes: deep-seated foundation failures and shallow subgrade deficiencies. Deep-seated failures comprise stability failures or slides, creep displacements, and consolidation settlements. The principal shallow subgrade problems are slope surface sloughs, mud pumping, ballast pockets, subgrade squeezes, frost action, clay swelling, soil collapse, liquefaction, and erosion. Deep-seated failures can result in dramatic, rapid slides of railroad embankments and other serious but generally localized track problems. The shallow problems, although less dramatic, affect greater and more continuous lengths of track and may therefore represent the more significant economic problem. Many of the shallow subgrade problems are associated with cohesive soil subgrades.

3.1 SUMMARY OF STABILIZATION PRACTICES

The measures available to stabilize track subgrades are listed in Tables 3-1 and 3-2. The stabilization methods may be separated into five groups: drainage, in-place modification, layer inserts, compaction, and embankment stabilization. The most important of the methods for railroad applications are described below.

Drainage

Drainage is the single most important and effective measure that may be employed to maintain substructure performance and embankment stability. Excess water will aggravate all of the subgrade problems that develop and will deteriorate ballast and subballast performance also. Sources of water affecting track substructure are precipitation, groundwater, and water drawn upward from the water table by capillary action. Erosion is directly related to drainage in that careless handling of drainage flows can undermine slopes and wash out tracks.

TABLE 3-1. APPLICATION OF STABILIZATION METHODS TO SUBGRADE PROBLEMS

STABILIZATION METHOD	SUBGRADE PROBLEMS											
	STABILITY	CREEP	CONSOLIDATION	SURFACE SLOUGHS	MUD PUMPING	SQUEEZES	BALLAST POCKETS	FROST ACTION	SWELLING	COLLAPSE	LIQUEFACTION	EROSION
DRAINAGE	X											
Lateral Drains				X	X	X	X	X	X		X	
Interceptor Drains	X			X				X				X
Cross Drains				X	X	X	X	X	X		X	
Horizontal Drains	X						X					X
IN-PLACE MODIFICATION												
Grouting	X	X		X			X			X	X	X
Lime Slurry Injection	X	X		X	X	X	X		X	X		
Deep Densification										X	X	
Preloading	X	X	X							X		
Prewetting									X	X		
Salting								X	X			
Electrochemical	X	X	X		X	X			X			
LAYER INSERTS												
Subballast				X	X	X		X	X			
Filter Fabric					X	X			X			
Impermeable Membrane	X							X	X			X
Insulation								X	X			
Capillary, Clay Interrupt								X				
COMPACTION			X	X		X				X	X	
Cement				X	X	X		X	X	X	X	X
Lime				X	X	X			X	X	X	
Bitumen				X	X	X		X	X		X	X
EMBANKMENT STABILIZATION												
Change Geometry	X	X	X								X	X
Retaining Structures	X	X										X
Vertical Reinforcement	X	X	X								X	
Machine Excavation	X	X	X					X	X	X	X	
Displacement	X	X	X									

TABLE 3-2. APPLICATION OF STABILIZATION METHODS TO TREAT SUBGRADE SOIL TYPES

STABILIZATION METHOD	UNIFIED SOIL CLASSIFICATION GROUP														
	GRAVEL				SAND				LOW PLASTIC			HIGH PLASTIC			
	GW - WELL GRADED	GP - POORLY GRADED	GM - SILTY	GC - CLAYEY	SW - WELL GRADED	SP - POORLY GRADED	SM - SILTY	SC - CLAYEY	CL - CLAY	ML - SILT	OL - ORGANIC	CH - CLAY	MH - SILT	OH - ORGANIC	PT - PEAT
DRAINAGE															
Lateral Drains	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Interceptor Drains			X	X	X	X	X	X	X	X	X	X	X	X	X
Cross Drains			X	X			X	X	X	X	X				
Horizontal Drains			X	X	X	X	X	X	X	X	X				
IN-PLACE MODIFICATION															
Grouting		X	X	X		X	X			X					
Lime Slurry Injection				X				X	X	X		X	X		
Deep Densification		X	X	X	X	X	X	X		X					
Preloading									X	X	X	X	X	X	X
Prewetting										X	X	X	X		
Salting			X			X	X		X	X	X		X		
Electrochemical												X	X	X	
LAYER INSERTS															
Subballast		X	X	X	X	X	X	X	X	X	X	X	X	X	X
Filter Fabric			X	X	X	X	X	X	X	X	X	X	X	X	X
Impermeable Membrane			X	X			X	X	X	X	X	X	X	X	
Insulation			X	X		X	X	X	X	X	X				
Capillary, Clay Interrupt			X	X		X	X	X	X	X	X				
COMPACTION	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Cement		X	X	X		X	X	X	X	X		X	X		
Lime				X				X	X	X		X	X		
Bitumen		X	X			X	X	X	X	X	X	X	X	X	
EMBANKMENT STABILIZATION															
Change Geometry									X	X	X	X	X	X	X
Retaining Structures			X	X			X	X	X	X		X	X		
Vertical Reinforcement									X	X	X	X	X	X	X
Machine Excavation									X	X	X	X	X	X	X
Displacement									X	X	X	X	X	X	X

Some general criteria are available for design of track drainage. The AREA Manual recommends that lateral drains be constructed at least 4 feet below the top of the subgrade. Drainage flows can be computed by analytic procedures that would suggest that lateral drains must be 5 feet to 6 feet or more below the top of subgrade for any material finer than medium sand unless underdrains are provided beneath the tracks.

Drainage of the track influences the design of the remainder of the substructure. Water content can alter the shear strength and allowable bearing pressure of a cohesive subgrade by a factor as great as ten. The shear strength of the subgrade determines the required thickness of ballast and subballast.

The two basic factors in design of a drainage system are establishment of drain geometry and selection of the type of drainage structure. Lateral drains run parallel to the track and are intended to carry surface runoff and to control groundwater level. Exposed ditch drains are the most common lateral drains, but buried lateral drains may be of particular value in areas of low relief, such as at grade crossings and in cut sections.

Cross drains may be installed perpendicular to the track in areas where lateral drains are insufficient, such as multi-track areas and yards. Typically, cross drains empty into lateral interceptors. Cross drains are installed from 2 feet to 10 feet below the top of the subgrade.

Interceptor drains are installed at the top of cut slopes to keep surface water from washing down and eroding or weakening the soils. In deep cuts, interceptors may be installed at middle points on the slope. Buried interceptors may be used to control groundwater behind a cut slope. Horizontal drains may be installed in a slope to complement or replace interceptors. These are 2-inch- to 3-inch-diameter pipes that are drilled into a slope from the face designed to carry groundwater flow only. They have been used on California highways to control slope stability problems.

There are three principal types of drainage structures: ditch drains, trench drains, and horizontal drains. Ditch drains are basically open channels designed and graded to carry the required flow. If seepage out of the trench is a factor, as for interceptor drains at the top of a slope, the ditch may be lined with pavement or membrane. Lining may also be required if high velocity flow would cause erosion.

Trench drains include pipe and French drains. A French drain is basically a trench filled with coarse stone or gravel. The stone collects the water as well as transmits the water along the trench through the voids in the stone. The principal difficulty in constructing French drains is that a filter must be installed around the coarse stone to prevent fine soil particles from washing into the coarse materials, clogging the pores, and reducing the flow capacity. Granular filters have been used for many years; however, acquiring a material with suitable gradation and installing the filter surrounding the stone are difficult. Recently filter fabric has been used around the stone to prevent movement of soil particles into the trench, so that a granular filter surrounding the course stone is unnecessary.

A pipe drain is simply a French drain with a pipe running through the bottom of the trench backfill. The pipe is perforated, slotted, porous, or laid with open joints to admit water. The pipe should be sized, usually 6 inches to 24 inches in diameter, to carry the required flow. The pipes should be fitted with manholes or accesses every 500 feet approximately to permit periodic cleaning, if required.

In-Place Modification

In-place modification methods treat subgrade soils in-situ. These methods are particularly attractive in that they often can be accomplished without removal of the track structure. However, some distortion of the track may require reestablishment of track geometry.

Grouting is used to reduce soil permeability and to increase shear strength. Penetration grouts permeate through the pores of the soil and are limited to applications in sands, gravels, and coarse silts. If the quantity of soil fines is excessive (greater than 10 to 20 percent), the rate of grout permeation is too slow to be practical. Sand-cement, cement, and clay grout suspensions are suitable for medium to coarse sands. Solutions, such as silica gels and some relatively exotic resins, must be used to grout finer soils; however, these grout materials are expensive. Compaction grouting involves injection of a stiff mortar into the soil that compresses the soil as the bulb of grout expands.

Railroads have used grouting for many years in two special applications. Sand-cement grout has been injected at the bottom of ballast pockets to stabilize further deterioration. The principal action of this process is to convert the ballast to concrete. This increases the load-spreading capacity of the ballast and limits further access of surface water to the ballast pocket and the subgrade. Cement grout is also used to stabilize embankment slides. Typical application is in cohesive soil fills that were placed by dumping without compaction. Cohesive soils are too fine-grained to accept permeation of the grout. Embankment grouting probably works by filling voids and fissures in the embankment, thereby stabilizing the water content of the fill and increasing the shear strength along the sliding surface.

Embankment grouting provides uncertain results. This is understandable in that it requires the grout to enter disconnected voids and fissures, and penetration may not be complete. Ballast pocket grouting has been used less often recently because the ballast is difficult to maintain after grouting.

Lime Slurry Pressure Injection (LSPI) - is a technique that involves injecting hydrated lime and water into clayey soils to reduce plasticity, to reduce the tendency to swell, and to increase strength. Typically, three grout pipes per track cross section are pushed through the ballast to a depth of approximately 10 feet, where the slurry is injected at successively shallower stages. The intent is to fill cracks and fissures in the clay to achieve maximum diffusion of lime into the soil. Typically, every second, third, or fourth crib is injected.

The effectiveness of LSPI stabilization programs is debatable. A few research programs have studied improvements achieved by LSPI, but conclusions are uncertain because of the effects of other simultaneous track improvements. It is questionable whether sufficient lime can be mixed with clayey subgrade soils by injection from discrete points to cause significant soil property improvement. Further study is needed in this area.

Salting has been adopted by the Canadian National Railway (CNR) as an effective means of limiting frost heaves. The method involves simply spreading granular rock salt at the top of track cribs where precipitation washes brine into the subgrade. The salt must be spread in a controlled amount only in areas where frost heaves are observed. Heave areas are identified by systematic survey. Drainage measures must be adequate prior to application of salt treatment. Eighty percent reduction in shimming for frost heaves was reportedly achieved by CNR with track salting. However, application of salt in areas where track crosses watersheds may be restricted to avoid chloride contamination of drinking water.

Layer Inserts

Layer inserts comprise man-made or natural materials that are placed in the structure to stabilize track substructure performance. Most inserts are intended to limit problems caused by unsatisfactory subgrade performance. The inserts may be placed at the top of the subgrade or at greater depths.

Subballast is the most frequently used layer insert. The function of the subballast is to prevent intrusion or mixing of ballast and subgrade. Subballast aids drainage by limiting vertical movement of surface water into the subgrade. For track rehabilitation, the principal drawback to subballast is that it must be placed in a thickness of at least 4 to 6 inches. This is impossible to accomplish without complete removal of the rails and ties. However, if the ballast and superstructure are to be completely removed, subballast should always be considered prior to reconstruction of the track.

Filter fabric is probably the method of railroad subgrade stabilization most frequently used today as part of maintenance or minor rehabilitation projects. Filter fabric is a porous, permeable cloth that is placed beneath the ballast or subballast to preclude the mixing of fine subgrade soil particles with coarse aggregates. Fabrics are used specifically to treat mud pumping and may also limit aggravation of ballast pocket formation. Fabrics also find use in lining drainage trenches and under riprap protection on slopes to prevent movement of soil while also permitting relatively free flow of water.

Filter fabrics can be made of many different plastics, but polypropylene, polyester, and polyethylene are the most popular. Fabrics used in railroad substructure applications typically weigh from 4 ounces to 12 ounces per square yard.

Filter fabrics have frequently been installed in association with ballast undercutting or sledding operations. In these instances, the rolls of fabric are attached to the ballast maintenance equipment and automatically unrolled as the equipment travels along the track. In addition to forming a particle separation layer between the ballast and subgrade, fabric also provides a tensile reinforcement layer that adds horizontal confinement to the ballast, increasing its strength and stiffness. It is also claimed that water moves laterally through the fabric, thereby draining the surface of the subgrade and stabilizing subgrade moisture content by a wicking action.

In common use on railroads for only six years, definitive criteria for filter fabric applications are yet to be developed. The critical physical properties of fabric appear to be tensile strength and elongation of fabric at break. Equivalent opening size of the fabric should not be greater than the D_{85}[1] of the subgrade soil. The U.S. Army Corps of Engineers recommends against using fabrics directly in contact with silts and clays unless the fabric is protected by a layer of sand. The thickness of ballast between the bottom of the ties and the fabric is a critical design factor. Clearly, enough ballast must be in place before tamping equipment is utilized to avoid puncturing the fabric. Six inches to 8 inches of ballast below ties is probably the minimum thickness before tamping, and 12 inches is preferable after tamping to limit ballast abrasion and puncturing. Most unsuccessful fabric installations have been associated with insufficient ballast between the ties and the filter fabric.

Anti-Frost Heave Measures - Frost heaving is a process that results in large upward movement of the ground surface (several inches to feet) as a result of formation of a lens of solid ice within the soil. Frost heaving requires subfreezing temperatures to penetrate the subgrade, a freezing zone above the groundwater table into which water is drawn by capillary action, and a soil that will support the frost heave phenomenon. The soil types most susceptible to frost heave are nonplastic silts, silty fine sands, and low plasticity cohesive soils. Because the magnitude of the heave is a complex function of all the factors mentioned above, it results in rough track due to differential heave from place to place. In addition to winter heaving, spring thaw often presents a more troublesome problem. Melting of the ice lens releases a considerable amount of water near the top of the subgrade that remains trapped by the underlying soil which thaws more slowly. The high moisture content leads to loss of subgrade strength, which can in turn

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[1] D_{85} is the particle size coarser than 85 percent of the total soil particles.

lead to overstressing of the subgrade by train traffic. Spring thaw represents the critical period of substructure strength evaluation.

Frost heaving may be treated by several methods: (1) replace the frost-heave-susceptible soil with clean, coarse-grained soil that will not draw water by capillarity, (2) provide insulation, either in the form of more ballast and subballast or in the form of foam insulating pads, or (3) stop or reduce the flow of water with either a layer of coarse soil (which cannot support capillary suction) or of clay (that has a low permeability and permits only slow upward water movement). Salt may also be applied to the tracks as described previously.

The principal difficulty with controlling the flow of water is that the interrupt layers must be placed below the freezing zone, which means several feet below the top of the substructure. This is generally impractical except in new construction or major reconstruction. Insulating layers do not have to be placed as deeply. However, they must be protected by enough ballast and subballast to limit stresses that would squeeze out the pores of the foam insulation and reduce the insulating property.

Compaction and Admixtures

Compaction is the rapid densification of soil accomplished by removing air-filled voids. Some coarse-grained soils may be compacted in a saturated condition if pore water can drain rapidly enough during the compaction process.

Generally, compaction should be carried out at the surface of the subgrade prior to placement of ballast and subballast, except on saturated cohesive soils. The purpose is to increase the strength of the soil near the surface.

To compact cohesionless soils, vibratory loading is the most effective method. Vibratory rollers and plates can densify soil to depths of from 6 inches up to several feet, depending on the size of the compactor, the gradation of soil, and the soil moisture content. Soil moisture plays a role in both "lubricating" the soil particles for easier densification and holding a cohesionless soil together by capillary action.

Low plasticity cohesive soils are more readily compacted by high shear stresses that may be supplied by heavy, rubber-tired rollers or by sheepsfoot rollers that contain protrusions that knead the soil. Moisture content is more critical for successful compaction of cohesive soils than for cohesionless soils. Highly plastic soils also require high shear stresses for compaction. Highly plastic soils will generally be in clumps or clods during placement. The intent of compaction is to break down all clods, so that voids between clods are removed. It is generally impossible to densify the clods, since the soils are nearly saturated and of low permeability. Highly plastic materials must be placed in thin lifts to assure uniform density. The optimum moisture content for placement is somewhat greater than the soil plastic limit.

Admixtures are used to improve the performance characteristics of soils, to aid compaction, and to increase stability and strength of soil over time after placement. Five admixtures are used most commonly to stabilize soils, particularly for pavement subbase construction: Portland cement, lime, fly ash, bitumen, and clay. The first two are the most popular by far. The steps in using a soil admixture are application or spreading of the admixture, mixing, moisture control, precuring, compaction, and curing. Since this process requires disturbance of the subgrade to mix in the admixture, these measures are applicable to new construction or rehabilitation only.

Portland cement may be used to stabilize nearly all soils but is best suited to treating poorly graded sands and gravels and silty soils with low plasticity. With 5 percent to 10 percent cement by weight, the soil cement mixture produces a lean concrete with a low strength of about 250 psi to 1000 psi. Lime is probably the first and most frequently used of the soil admixtures. Lime is particularly effective in treating cohesive soils in that it decreases plasticity, improves workability, reduces swelling potential, and increases shear strength of the soils. Lime in combination with clay minerals produces cementing compounds similar to Portland cement. Lime has advantages over cement in that the modified soil may remain moist for a long period of time before compaction and will continue to gain strength over time, even if disturbed after placement. Cement, on the other hand, must be compacted within two hours of moistening to produce a rapid strength increase, thereby permitting more rapid construction over the stabilized layer. Sometimes lime and cement are used in combination--lime for workability and cement for rapid strength increase.

Bitumen is suitable to stabilizing granular soils with moderate fines content and low plasticity. It is more expensive than Portland cement but produces a less permeable soil layer and may remain self-healing for a period of time. Fly ash and clay are sometimes added to clean granular soils to impart some cohesion. They may be used in combination with lime in soils that contain no clay to provide a necessary component in the lime cementing reactions.

Admixture modified, compacted soils are particularly suitable where high quality aggregates are economically unavailable. For low bearing capacity subgrades, stabilizing the subgrade soil in-place with an admixture may be more economical than providing the equivalent thickness of imported ballast, subballast, or blanket. The admixtures also facilitate construction workability and add some special properties, such as low permeability and trafficability, to the soil.

Embankment Stabilization

Embankment stabilization measures are intended to treat deep-seated types of failures rather than shallow subgrade problems. The four basic methods grouped under this heading are change of embankment or slope geometry, retaining structures, vertical reinforcement, and replacement of the unsatisfactory subgrade or foundation soil, either by machine excavation or by displacement with embankment fill.

If an embankment is constructed higher than can be accommodated by the strength of the foundation, the resulting embankment slide can be counterbalanced by construction of berms or by flattening side slopes. The stability of excavations into soft soils may be increased by flattening the slope uniformly or by benching. If recognized prior to construction, lightweight fill may be used in an embankment to reach a required height while exerting a lower stress on the foundation.

Retaining structures have been used for many years to stabilize embankment slides. Poles or ties may be driven at the crest of an embankment to restrict slope movements. Sometimes the horizontal reaction is developed by cantilever action in deeper, stable soils, or more often two rows of poles are driven on either side of the embankment and then tied together with rods or cables.

The principal advantages of these measures are that they can be installed quickly and can be modified if additional stabilization force is required. More elaborate and permanent retaining structures may also be used to add stability to embankments or cut slopes. These are typically expensive structures that require careful engineering design.

Vertical reinforcement has been used to stabilize embankments and foundations over soft soils. The vertical reinforcing elements are installed through a shallow, limited-thickness layer of soft, compressible soil to bear on a suitable stratum. Reinforcing elements may be piles with discontinuous pile caps, post-hole piles, lime-soil columns, Root Piles®, stone columns installed by a Vibroflot®, sand columns installed in a driven spud hole, or sand compaction piles. Some of these methods have been used to support embankments in Europe and to provide foundations for structures. By transferring the embankment load through the soft layer, stability of the embankment is increased and consolidation settlements are reduced.

Finally, embankment stability problems may be stabilized by removing the subgrade soil that is causing the movements. This type of stabilization is only practical for new construction. Excavation by standard earthmoving equipment is effective, but relatively expensive. Dewatering the excavation is sometimes a major consideration. Sometimes embankments are placed in such a way that the fill intentionally causes a failure in the soft soil, producing a mud wave. The fill then displaces the soft soil. Buried explosive charges can also be used to help displace the soft soil. Where the width of right-of-way exists, displacement is sometimes cheaper than machine excavation, even though a greater quantity of fill may be required and the density and settlement of the fill over time may be greater.

3.2 ASSESSMENT OF STABILIZATION PRACTICES

The subgrade stabilization methods described can be divided into four categories: (1) methods that have been used in railroad applications for which adequate design criteria exist, (2) methods that have been used in railroads but which require further development to determine proper application and to assess improvements brought about by stabilization, (3) methods that appear to be promising for application to railroads, and (4) methods that would only rarely be applicable to railroad subgrade stabilization. To evaluate and compare stabilization methods, it is not only necessary to evaluate whether a method will work, but also to assess how much improvement stabilization will provide in terms of replacing other elements of the substructure, such as some thickness of ballast, or in terms of reducing maintenance costs and extending track substructure and hardware life. Only with these types of quantitative data can the economic decision be made on whether to stabilize and by what method. The quantitative data necessary to make these types of evaluations do not exist presently, even for those methods of stabilization that have become widely used in railroads. Following are detailed assessments of stabilization methods and the technological developments that have been identified for stabilization methods belonging to categories 2 and 3. Only those methods that can be applied to track already in place will be assessed.

Stabilization Methods Used on Railroads

The following are brief assessments of the technological developments needed for stabilization methods that are currently applied to track subgrade stabilization by North American railroads.

Drainage - Rational design and standard design practices for drainage systems are well developed at this time. Critical assessment is needed to relate required depth of groundwater and surface water control and subgrade soil classification to development of shallow subgrade failures (mud pumping, squeezes, etc.).

Grouting - The particular uses of grouting in railroad track stabilization are poorly understood. Grouting of ballast pockets, although attractive from the point of view of limited disruption, probably results in a track with uneven resilient properties and often cements the entire ballast section. Although no critical evaluation of this method was discovered, it has fallen into disuse and probably deserves no further consideration.

Embankment grouting with cement and sand is still in use by railroads to stabilize fill slides in cohesive soils. This application of cement grout by railroads is different from the conventional applications of permeation grouts since the cohesive soils cannot accept any significant quantities of grout. A study of the mechanism of fill stabilization by grouting should be undertaken to develop criteria for applications of grouting and quantitative estimates of performance improvement.

Lime Slurry Pressure Injection (LSPI) - LSPI appears to have as many detractors as proponents. The mechanism of improvement is poorly understood--it is simply judged not possible to inject enough lime into a cohesive soil to produce significant improvement in subgrade performance. Successful LSPI treatment has been irregular. Studies are needed to determine the criteria for application of LSPI and the means of estimating improvement in subgrade properties achieved by LSPI.

Salting - Criteria for evaluation of surface salting to treat frost heaves have been developed based on a limited investigation by the Canadian National Railway. Further studies are needed to confirm the initial findings and to refine the criteria with respect to subgrade type and environmental conditions necessary for successful application.

Filter Fabric - Filter fabric has received the most attention recently as a substructure stabilization method. However, criteria are yet to be developed concerning acceptable fabric properties, such as tensile strength, opening size, material, manufacturing process, etc., and suitable installation details such as minimum depth of ballast cover. Systematic evaluation of completed installations would probably supply the necessary data. The studies would be complicated by the influences of other track improvements installed at the same time as the fabric. Some controlled experiments would assist in the evaluation.

Compaction and Admixtures - The improvement in material properties derived from compacting soils when placed as fill is so great in comparison to the cost that adoption of compaction for fills is nearly universal. Use of admixtures requires more careful evaluation to balance benefits and costs. Lime stabilization of clay subgrades is routinely carried out by some railroads. Criteria are needed to relate thickness and shear strength of the stabilized layer to thickness design of the ballast and subballast. Several mix design methods have been developed for each of the admixtures. A mix design method must be developed to coordinate with a method of substructure design as discussed in Section 4.

Stabilization Methods Adaptable to Railroads

The following methods of subgrade stabilization have been used successfully in other applications and are judged to be promising for railroad applications.

Electrochemical Stabilization - Electrochemical stabilization is judged suitable for nondisruptive treatment of highly plastic clay subgrades subject to swelling and shrinking, as well as for treatment of other shallow subgrade problems. The electrodes may be placed far enough apart to be installed at either end of the ties. The method is relatively expensive but not well proven; field trials are required.

Bituminous Spray - Application of bituminous spray to the surface of the subgrade would appear to be an economical means of waterproofing the subgrade surface as part of a ballast undercutting or sledding operation. The bitumen membrane would not be so effective as to trap all evaporation and may therefore avoid the softening effect observed when waterproof plastic membranes are used to cover ground areas. The beneficial effects of the spray must be studied in field trials.

Frost Heave Mitigation - The measures to limit frost heave have been developed for pavement engineering. Analogous design criteria for railroad practice must be developed so that the required thickness of ballast and nonfrost susceptible soil below the track surface can be determined. Insulation below track has been used to limit frost effects on Norwegian and Soviet railways. Criteria for application and design of insulation installations for heavy North American axle loads must be developed.

Vertical Reinforcement - Some of these methods appear attractive for both new construction and rehabiltation. Sand columns installed in augered rather than driven holes would add both vertical drainage and reinforcement. A lime column rig could be developed for operating between the ties. A significant quantity of lime could be installed by this method. A demonstration project varying spacing and depth of lime columns is the first step needed in developing this procedure.

4. TRACK SUBSTRUCTURE DESIGN AND EVALUATION

The purpose of the railroad track structure is to allow the safe and economical passage of trains. As such, its two principal functions are to:

a. Provide a guideway controlling the vertical and horizontal alignment of the train; and

b. Receive rail vehicle wheel loads and distribute them to the natural soils underlying the track within their allowable working stresses.

The conventional railroad track structure is composed of many components, including rails, fasteners, crossties, tieplates, ballast, subballast, and the subgrade. These components perform as a system. If one component of the system becomes defective, other components may become overstressed. The interactions among track components when loaded are complex. This complexity has made it difficult to study the role of an individual track component.

4.1 SUMMARY OF DESIGN AND EVALUATION PRACTICES

Design of railroad track and track substructure requires procedures that consider the applied loading, earth material and track structure properties, and track geometry. These factors are summarized below.

Track Loading Conditions

Static and dynamic, vertical, lateral, longitudinal, and thermal loads are transferred to the track structure and should be considered in substructure design.

Vertical Load - The static vertical load is the load acting on the rail head from a stationary vehicle. The trend on North American (United States and Canada) railroads has been toward bigger cars and increased wheel loadings, with 100-ton cars becoming the rule rather than the exception. In the period from 1955 to 1978, the average carrying capacity of cars increased by 43 percent. For the most part, these larger wheel loads are moving over track structures designed for significantly smaller wheel loads. The net result has been a rapidly increasing rate of track deterioration. While no conclusive proof has been developed, the general consensus among maintenance-of-way engineers is that 100-ton nominal car loads have led to increased rate of ballast settlement, increased rail wear due to plastic flow, increased rate of rail defect occurrence, increased rate of crushing of wood caps on timber trestles, and increased overall track maintenance costs.

Hay[1] reports that considerable foreign experience indicates that wheel load/diameter (W/D) ratios in the range of 550 to 650 pounds per inch are economical, while W/D ratios of 800 pounds per inch appear to be too high for economical performance. The typical 100-ton car W/D ratio is 913 pounds per inch.

Dynamic loads are imposed on the track in the form of impact loadings and vibrations. Vertical and lateral impact loadings such as rock and roll, truck hunting, nosing action, wheel flats, and vertical bounce produce severe dynamic loading on the track. Dynamic forces resulting from impact loadings are normally considered in track design by increasing the design static wheel load by a given factor, usually 2 for wood ties and 2.5 for concrete ties in North American practice.

The effects of vibrations are poorly understood and generally not accounted for in track substructure design. Vibrations from dynamic wheel loads cause permanent deformations in the substructure due to densification of ballast and granular soils and consolidation settlement of cohesive soils. Vibration energies are damped by the substructure by both inelastic deformations and "system" damping caused by radiation of energy into the substructure. High frequency vibration waves attenuate quickly in the subgrade, and their magnitude is only appreciable near the subgrade surface. Vibrations of principal concern are inaudible low frequencies up to 16 Hertz (Hz) generated by repeated static loadings. Low frequency energies are not strongly damped in the ground. Low frequency vibrations are in the range of the characteristic natural frequencies of the track-substructure systems and can induce resonance and relatively large dynamic displacements.

The effects of vibrations can be limited if the vibration energy is reduced by insulating the track with low frequency shields. The insulating body that supports the vibrating body must have a significantly lower characteristic frequency than the input vibration. Spang[2] (1972) reports that a characteristic frequency of the insulating material of one-quarter of the input frequency is usually sufficient insulation. The German Federal Railway has experimented with hard rubber tie pads between the ballast and tie, and the rail and tie with good results. Work is being done by the German Federal Railway and others[3] to develop better insulating materials for rail fasteners and tieplates.

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[1]W. W. Hay, "Track Structures for Heavy Wheel Loads," Proceedings, of the 12th Annual Railroad Engineering Conference, Pueblo, Colorado, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, Report No. FRA/OR&D 76-243, October 1975, pp. 27-36.

[2]J. Spang, "Deformation of Railroad Track Base and Its Stabilization," Eisenbahntechnische Rundschau, Vol. 21, No. 10, 1972, p. 376.

[3]R. H. Prause et al., An Analytical and Experimental Evaluation of Concrete Cross Tie and Fastener Loads, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, Report No. FRA/ORD 77/71, December 1977, 356 pp.

Lateral Loads - The track structure must resist thermal loads on unoccupied track and combined thermal and lateral wheel loads on occupied track. Lateral wheel loads are caused by the lateral component of the frictional force between the wheel and rail and by the lateral force applied by the wheel flange against the rail. "Hunting" of trucks and "nosing action" of locomotives are typical lateral wheel load mechanisms. Thermal loadings are produced when continuous welded rail (CWR) is exposed to solar heating and ambient temperatures that are different from the installation temperatures. Compressive forces develop when the temperature is above installation temperature, and tensile stresses develop below installation temperatures.

The only work discovered on evaluation of lateral loads on loaded railroad track was carried out on the French National Railway[4]. The studies were based on field measurements with a special "derailer wagon" that applied horizontal force to track loaded by the car. However, lateral resistance of unloaded track generally is more critical due to the effect of thermal loading.

To evaluate the lateral force induced on curves of unoccupied track by thermal loading, Magee[5] developed an equation that is included in the AREA Manual as follows:

$$P_f = 0.441\,(D_c)\,(\Delta T)$$

where:

P_f = total lateral force (pounds per foot of track),

D_c = degree of track curvature

ΔT = temperature change (°F) above rail-laying temperature.

When used on perfectly straight track, this equation gives a lateral force of zero, which is true if there are no alignment faults, crippled rails, or angular welds. This equation may be applicable to areas where the regional temperature does not vary widely or where the consequences of track buckling or rail breaks are not severe. For critical applications, a more thorough investigation of induced thermal loads, susceptibility of the track to thermal

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[4]F. Amans and R. Sauvage, "Railway Track Stability to Transverse Stresses Exerted by Rolling Stock. A Theoretical Study of Track Behavior. A Practical Method for Determining the Resistance of Track to Transverse Stresses Exerted by Rolling Stock," Bulletin of the International Railway Congress Association, Vol. 46., No. 10, October 1969, pp. 701-702.

[5]G. M. Magee, "Welded Rail In Bridges," Railway Track and Structures, November 1965, pp. 24-26.

loads, and susceptibility of the track to thermal track buckling should be made. Extensive work by A. D. Kerr[6] provides a basis for evaluating thermal track buckling in unoccupied track.

Longitudinal Loads - Longitudinal loads are also developed as a combination of train motion loads and thermal loads. Rail wave action, train brake effect, and tractive effort are forms of train motion loads. Train brake action produces the largest longitudinal train motion load, and the fundamental equation, F = ma, can be used to determine the load. For example, for a train to decelerate 0.5 miles per hour per second on level and tangent track, the braking system must exert 4,560 pounds per 100 tons. The required forces will be increased if the train is descending a grade. The AREA Manual recommends a longitudinal force equal to 15 percent of the live static wheel load for design longitudinal loads induced by train motion.

No criteria are presently given in the AREA Manual for evaluating the magnitude of thermally induced longitudinal loadings. However, the previously referenced work by Kerr has provided a design procedure to evaluate the maximum rise in temperature that unoccupied continuous welded rail track can tolerate without buckling.

Track Geometry

The ultimate goal of track substructure design is to develop a track structure that will maintain optimum track geometry. Tests conducted by R. H. Prause on the Florida East Coast Railway indicated that one of the principal modes of track degradation was permanent track geometry change.[7] Prause also found that long-term deterioration of track geometry was responsible for the major portion of track maintenance costs and reduced safety factors.

A small resilient deflection of the track structure as the vehicle moves is necessary and desirable to absorb energy and reduce shock to track structure components and rolling stock. Limits of resilient deflections for various levels of track structure performance were presented by Lundgren[8] and Prause[9]

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[6]A. D. Kerr, Thermal Buckling of Straight Tracks; Fundamentals, Analyses, and Preventive Measures, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, Technical Report No. FRA/ORD-78/49, September 1978, 58 pp.

[7]R. H. Prause et al., Op. Cit., pp. 265-267.

[8]J. R. Lundgren, G. C. Martin, and W. W. Hay, "A Simulation Model of Ballast Support and the Modulus of Track Elasticity," University of Illinois, Urbana, Illinois, September 1970, pp. 15-16.

[9]R. H. Prause et al., Op. Cit., p. 27.

and are shown on Figure 4-1. Resilient track displacements above acceptable limits cause rapid, permanent distortions of track geometry and contribute to fatigue failures of track superstructure components.

Acceptable track geometry and operating speed criteria have been established by the Federal Railroad Administration (FRA), in Track Safety Standards. The FRA standards are minimum criteria for safe performance and in some instances are below those established by operating railroads for economical performance. Table 4-1 presents a version of geometry criteria advocated for the Northeast Corridor Improvement Project (Howell et al., 1975) and FRA minimum standards for 110 mph, Class 6 track. Geometry criteria established for high speed operations by the Japanese National Railway and the British Rail are shown in Table 4-2. The limits shown in Table 4-1 and 4-2 are used to establish geometry during lining and tamping operations, to determine when maintenance is required, and to evaluate when slow-orders are necessary due to deteriorated track geometry.

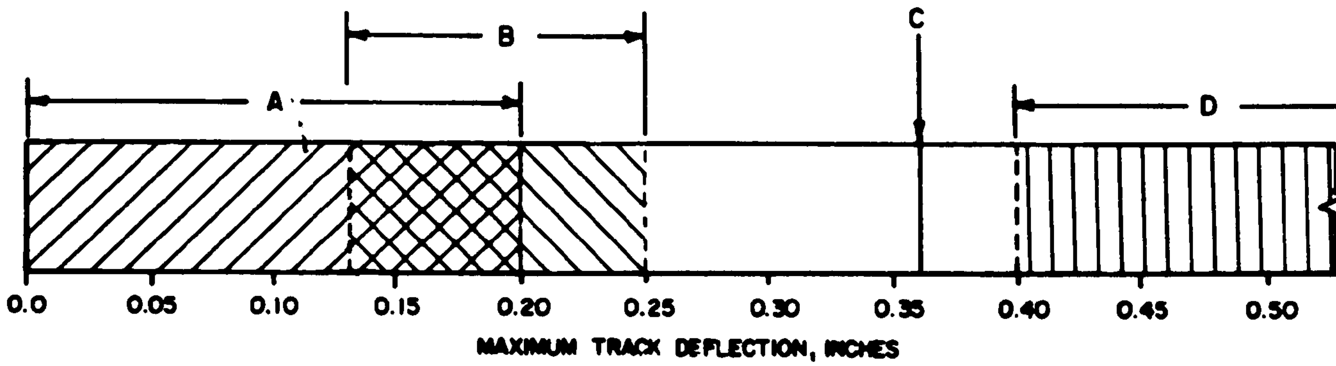
Design and Analysis for Vertical Loads

Railroad track substructures experience repeated, transient loads from trains. When subjected to repeated loads, granular materials, such as railroad ballast and subballast, undergo both resilient and residual deformations during each load cycle. Material behavior observed in laboratory tests indicates that nearly all of the vertical strain that occurs is resilient and is recovered after each load cycle with very small plastic strains accumulating at a small, decreasing rate. The resilient response of substructure materials to cyclic loading is most frequently described by the resilient Young's modulus, E_r. Residual behavior of substructure materials is frequently represented by the residual axial strain that occurs after a given number of cycles for a particular set of test conditions.

The cyclic substructure behavior described above has been observed in the field at the DOT Facility for Accelerated Service Testing (FAST) track in Pueblo, Colorado. Selig et al.[10], measured the resilient and residual response of the ballast, subballast, and subgrade layers to dynamic loading. No other record of this type of field measurement was found in the literature, and as such, the FAST measurements have provided the first data on the actual response of substructure layers to dynamic loading. A general summary of some basic inferences developed from the FAST measurement program is presented in Table 4-3.

Research into track substructure response, i.e., the behavior of ballast, subballast, and subgrade materials and structures, has included both laboratory and field test programs. Laboratory-measured substructure element behavior

[10]E.T. Selig et al., Status Report - Ballast Experiments, Intermediate (175 MGT) Substructure Stress and Strain Data, U.S. Dept. of Transportation, Transportation Test Center, Interim Report, September 1979, pp. 3-79, FRA/TTC-81/09.



RANGE	TRACK BEHAVIOR
A	Deflection range for track which will last indefinitely.
B	Normal maximum desirable deflection for heavy tracks to give requisite combination of flexibility and stiffness.
C	Limit of desirable deflection for track of light construction ($\leq$ 100 lb rail).
D	Weak or poorly maintained track which will deteriorate quickly.

Values of deflection are exclusive of any looseness or play between rail and plate or plate and tie and represent deflections under load.

Reproduced from "A Simulation Model of Ballast Support and the Modulus of Track Elasticity," by Lundgren et al., Year of First Publication: 1970, p. 16.

FIGURE 4-1. TRACK DEFLECTION CRITERIA FOR DURABILITY

TABLE 4-1. PARAMETERS FOR MAINTENANCE SCHEDULING AND QUALITY CONTROL EVALUATION: NORTHEAST CORRIDOR PASSENGER RAIL SERVICE

Parameter Description	Construction and Maintenance Quality Control Limit	Maintenance Program Demand Limit	Limit* Requiring Slow Order Consideration
TRACK SURFACE			
Runoff in 31'	1/8"	3/8"	1/2"
Deviation in profile at mid-ordinate of 62'	1/8"	1/4"	1/2"
Deviation from designated elevation on spirals	1/8"	1/4"	1/2"
Variation in cross level in 31' on spirals	1/8"	3/8"	1/2"
Deviation from zero level on tangents or from designated elevation on curves	1/8"	3/8"	1/2"
Difference in cross level within 62' on tangents and curves	1/8"	3/8"	5/8"
ALIGNMENT			
Deviation of mid-offset from 62' line-tangent	1/8"	1/4"	1/2"
Deviation of mid-ordinate from 62' chord-curve	1/8"	1/4"	3/8"
Gauge (4'- 8 1/2")			
Tangent			
Minimum	4'8-3/8"	4'8-1/8"	4'8"
Maximum	4'8-9/16"	4'8-5/8"	4'8-3/4"
Curve			
Minimum	4'8-3/8"	4'8-1/8"	4'8"
Maximum	4'8-5/8"	4'8-7/8"	4'9"

*Limits equivalent to tolerances for F.R.A. Track Safety Standards Class 6 Track, rated for 110 m.p.h. passenger and freight service.

Reproduced from Northeast Corridor High-Speed Rail Passenger Service Improvement Study, Task 3 - Track and Structures Standard Development, p. 115, by R. P. Howell et al., U.S. Dept. of Transportation, Federal Railroad Administration. Year of first publication: 1975.

TABLE 4-2. TRACK GEOMETRY CRITERIA FOR JAPANESE AND BRITISH RAILWAYS

Track Geometry Parameter	Japanese - 130-160 MPH Application								British Rail	
	Post Work Tolerance		Maint. Work Sched. Tol.		Good Ride Comfort		Slow Down Tolerance		Maximum Target	
	mm	In	mm	In	mm	In	mm	In	In	
Long. level measured by 10M (32.8') chord	4	3/16	5-6	3/16-1/4	7	1/4	10	3/8	1 in 500 (over 10 ft.)	1 in 750
Alignment measured by 10M (32.8') chord	3	1/8	3-4	1/8-3/16	4	3/16	7	1/4	±1/8	±3/32
Alignment on curve measured by 10M (32.8') chord	3	1/8	-	-	-	-	-	-	±1/8	±3/32
Alignment on curve measured by 20M (65.6') chord	-	-	4	3/16	5	3/16	8	5/16	-	-
Gage	+2 -2	+1/16 -1/16	+5 -3	+3/16 -1/8	+6 -3	+1/4 -1/8	+10 -6	+3/8 -1/4	±1/8	±1/16
Distortion measured by 2.5M (8.2') axis distance	3	1/8	3	1/8	5	3/16	5	3/16	-	-
Cross Level	3	1/8	5	3/16	5	3/16	10	3/8	-	-
Desirable X Level over 10'	-	-	-	-	-	-	-	-	±1/8	±1/16
Cant	-	-	-	-	-	-	-	-	+3/8	±1/4
Joint Dips over Six Sleepers	-	-	-	-	-	-	-	-	-3/8	-1/4

Reproduced from Northeast Corridor High-Speed Rail Passenger Service Improvement Study, Task 3 - Track and Structures Standards Development, p. 116, by R. P. Howell et al., September 1975.

TABLE 4-3. FACTORS AFFECTING SUBSTRUCTURE RESPONSE AT FAST

PARAMETERS	RESILIENT BEHAVIOR	RESIDUAL BEHAVIOR
Ballast Type Granite Limestone Traprock	Strains in granite and limestone ballast significantly higher then those in traprock ballast. Subballast strains below traprock higher than those below limestone or granite. Subgrade deflection below granite ballast less than below traprock or limestone.	Accumulated strains in ballast approximately equal for all three ballast types. Strains in subballast below traprock were higher than those below granite or limestone. Subgrade deflections approximately equal with those below granite highest.
Ballast Depth 15-inch vs. 21-inch	Strains in 21-inch ballast layer slightly higher than 15-inch layer. Subballast strain below 15-inch ballast layer slightly higher than 21-inch layer. Subgrade deflections approximately equal for both thicknesses.	Strains in 21-inch ballast layer from 0.5 to 0.8 higher than those in 15-inch layer. Subballast strains approximately equal below 15 and 21-inch ballast layers. Subgrade deflections approximately equal below both layers.
Tie Type * Concrete vs. Wood	Ballast strains below hardwood ties significantly higher. Subballast strains below concrete ties significantly higher. Subgrade deflections approximately equal.	Ballast strains approximately equal. Subballast strains approximately equal. Subgrade deflections approximately 1.7 to 1.9 higher below concrete ties.
Track Geometry Tangent vs. Curved	Ballast strains slightly higher below tangent track. Subballast strains significantly higher below tangent track. Subgrade deflections approximately equal.	Conflicting ballast strain data. Subballast strains approximately equal. Subgrade deflections approximately equal.

* Note comparison not strictly valid since tie spacings and rail connections were different: Concrete ties : 24 inches center to center, CWR Rail; Wood ties : 19.5 inches center to center, Jointed Rail

Source: Elastic and Inelastic Deformation Response of Track Structure Under Train Loads, by C.W. Adegoke, Ph.D. Thesis, State University of New York at Buffalo, December 1978, pp. 148-157.

provides quantitative data on the effects of such parameters as material type, gradation, density, and confining pressure on the stresses and strains developed in substructure materials. These data are valuable in developing a proper understanding of substructure material behavior under load and in properly characterizing materials in analytical computer models of substructure response. Field measurement programs are valuable in that they provide both an understanding of substructure material behavior and data for validation of analytical computer models. Such validation of the computer models is needed before they can be applied with any degree of confidence.

Current North American Design Practice - Current design practice in North America is based predominantly on experience. This experience has resulted in the development by several North American railroads of standard designs for ballast and subballast depths, as shown in Table 4-4. The ballast and subballast depths shown in Table 4-4 range from 6 inches to 12 inches and from 4 inches to 12 inches, respectively. These variations are probably due to different soil and environmental conditions in different regions. Increases in ballast and subballast depths over the minimums due to weak subgrade conditions are allowed.

The adoption of standardized design sections for track for different areas and loading conditions is, in our opinion, a reasonable procedure. However, it should be recognized that such standard designs should be considered as envelope procedures. That is, as long as subgrade conditions exceed some minimum level of performance, or lower envelope, the standard design can be expected to provide a satisfactory track design. The principal challenges in applying this type of procedure are to identify conditions that fall below the envelope and to evaluate design modifications for these substandard conditions.

Procedures currently adopted by railroads for recognizing conditions where standard sections will not suffice, and methods used to evaluate whether and how much additional substructure material is necessary, are not clear. Rational testing and analytical methods do not appear to be used generally.

The beam-on-elastic foundation analysis method is the best known of those methods used in North America today. This method has several limitations in that (a) it does not adequately represent the performance of individual track components, (b) it evaluates resilient stresses and deformations only, and (c) it does not consider repeated dynamic loading or residual displacement of components. The track modulus, u, is used to represent the combined stiffness of ties, ballast, subballast, and subgrade. Many factors affect the value of u, and it is difficult to evaluate the influence of any one element on the magnitude of the combined track modulus.

In current North American design practice, little attention is paid to determining the type, strength, and conditions of subgrade soils and to incorporating these properties into design analyses. The fundamental criterion used in track substructure design is to limit the pressure on the subgrade to an amount the subgrade can support. AREA recommends a limit of 20 psi. This, however, may lead to performance difficulties in loose fine sands, clays,

TABLE 4-4. SPECIFICATION FOR MAINLINE TRACK FORMATION

RAILWAY	SUBBALLAST	BALLAST
Canadian National Railway	Minimum of 12 in. (300 mm)	12 in. (300 mm)
Canadian Pacific LTD	--	12 in. (300 mm)
Southern Pacific Transportation Co.	Minimum of 6 in. (150 mm)	Minimum of 6 in. (150 mm)
The Atchison, Topeka and Sante Fe Railroad	12 in. (300 mm)	12 in. (300 mm)
Seaboard Coast Line Railroad	4 in. (100 mm)	Minimum of 6 in. (150 mm)
Union Pacific Railroad	6 in. (150 mm)	8 in. (200 mm)
Illinois Central Railroad	12 in. (300 mm)	12 in. (300 mm)
Southern Railway System	12 in. (305 mm)	12 in. (305 mm)
AREA Recommendations	Minimum of 6 in.	Minimum of 12 in. (Mainline Track) Minimum of 6 in. (Other Track)

silts, and dumped uncompacted fills since the allowable bearing pressure of soils varies. In our opinion, this area of track substructure design requires further study.

Foreign Design Practice - Review of foreign practice has revealed three basic substructure analytical and design methods to determine substructure layer thicknesses: the multi-layer elastic methods used by railroads in Germany, Hungary, Czechoslovakia, and Japan; the threshold stress approach used in Great Britain; and an effective stress analysis used in India. These methods are similar in that:

a. Each railroad uses empirically based, analytic methods to evaluate the thickness of ballast and subballast materials needed in the substructure. Except for the Indian railroad approach, the methods are based on flexible highway pavement design procedures that use elastic properties of the various layers to determine the thickness of ballast and subballast layers. These methods are used with experience gained from quantitative observations and evaluations of in-service track performance to develop successful track and substructure designs. The design thicknesses are adjusted for environmental considerations, e.g., freeze-thaw, swell potential, and moisture conditions, based on field experience.

b. Each method is based on the fundamental design criterion of limiting the stresses on the subgrade soils to an allowable level, one which the subgrade can support without excessive deformations.

c. The simple Boussinesq elastic stress distribution for a semi-infinite half-space was judged adequate for estimating the stresses below the ties. A modified tie contact pressure distribution gave better results than a single point load. The justification for using the Boussinesq theory is that the variations in the magnitude of stresses measured in the substructure make a more rigorous solution unnecessary.

d. Each method emphasizes the importance of classifying the subgrade soils and determining their strengths and deformation properties. Typical methods include field plate load and California Bearing Ratio tests and laboratory static and cyclic triaxial shear tests on undisturbed tube samples of subgrade soils. The field and laboratory tests are performed under "worst case" conditions, usually saturated, spring-thaw conditions for field tests, and saturated, undrained tests in the laboratory.

e. Standard top ballast sections, with thicknesses ranging from 10 to 20 inches, are used by each of the foreign railroads. The thickness is based on the minimum amount needed to spread the loads to a granular subbase while providing sufficient resilience, drainage, and workability for maintenance purposes. Additional thicknesses of material needed for stress distribution are provided by the subballast layers over lower quality subgrades.

TABLE 4-5. SAFE AVERAGE SUBGRADE BEARING PRESSURES

SUBGRADE DESCRIPTION	ALLOWABLE PRESSURE BELOW TRACK (PSI)
Alluvial Soils	Below 10
Made Grounds, Not Compacted	11 - 15
Soft Clay, Wet or Loose Sand	16 - 20
Dry Clay, Firm Sand, Sandy Clay	21 - 30
Dry Gravel Soils	31 - 40
Compacted Soils	41 and over

Source: C. W. Clarke, "Track Loading Fundamentals-3," The Railway Gazette, Vol. 106, February 8, 1957, p. 159.

SUBGRADE DESCRIPTION	IN-PLACE CONSISTENCY	ALLOWABLE PRESSURE BELOW TRACK (PSI)
Well graded mixture of fine and coarse grained soil: glacial till, hardpan, boulder clay (GW-GC, GC, SC).	Very Compact	65 - 100
Gravel, gravel-sand mixtures, boulder-gravel mixtures (GW, GP, SW, SP)	Very Compact	55 - 85
	Medium to Compact	40 - 60
	Loose	25 - 50
Coarse to medium sand, sand with little gravel (SW, SP)	Very Compact	30 - 50
	Medium to Compact	25 - 30
	Loose	15 - 25
Fine to medium sand, silty or clayey medium to coarse sand (SW, SM, SC)	Very Compact	25 - 40
	Medium to Compact	15 - 30
	Loose	8 - 15
Fine sand, silty or clayey medium to fine sand (SP, SM, SC)	Very Compact	25 - 30
	Medium to Compact	15 - 25
	Loose	8 - 15
Homogeneous inorganic clay, sandy or silty clay (CL, CH)	Very Stiff to Hard	25 - 50
	Medium to Stiff	8 - 25
	Soft	4 - 8
Inorganic silt, sandy or clayey silt, varved silt-clay-fine sand (ML,MH)	Very Stiff to Hard	15 - 30
	Medium to Stiff	8 - 25
	Soft	4 - 8

Source: Soil Mechanics, Foundations, and Earth Structures, pp. 7-11-12, U.S. NAVFAC Design Manual DM-7. Year of first publication: 1962.

SUBGRADE DESCRIPTION	ALLOWABLE PRESSURE BELOW TRACK (PSI)
Coherent or fragmented rock	57
Banks of boulders	50
Gravel	43
Dry Clay and pug	28 - 36
Fine sand	14 - 21
Wet clay and pug	11 - 14

Source: "Determining the Depth of Ballast", p. 142, by B. Milosevic. Year of first publication: 1980.

f. Standard substructure sections were developed by each railroad using one of the analytic methods mentioned above and experience. Some of these standard sections are summarized in Table 4-6. The standard sections are adjusted to the type of subgrade soil, with thicker sections over weaker subgrades, and with filter and stabilized layers over silty or cohesive subgrades.

g. Each method emphasizes the importance of providing a high quality drainage system for removal of surface and subsurface water.

Like North American practice, the principal criterion in foreign design practice is to limit the peak resilient stress on the track subgrade so that bearing capacity failures and excessive permanent settlement are avoided. Also like North American practice, standard track sections have been developed, and experience plays a large role in determining which section to use with specific subgrade conditions.

Unlike North American railroads, however, practical analytical methods have been developed by foreign railroads and are used for determining the required thicknesses of ballast and subballast layers, considering both the type and properties of local subgrade materials. In addition, after track sections are built or rehabilitated, track and substructure performance is monitored so that proper evaluation of particular substructure designs can be made.

Comparison of standard loadings and substructure sections used on North American and foreign railroads is revealing. The common peak static wheel load on North American track today is 33,000 pounds for a 100-ton car. Loads of 39,400 pounds (125-ton car) and 27,500 pounds (77-ton car) are also encountered. This means that North American track structures experience static loads 50 to 80 percent higher than the approximately 22,000-pound wheel load used by most foreign railroads. For these significantly larger loads, North American railroads use substructures (ballast plus subballast) ranging from 12 inches to 24 inches in total thickness. However, for their substantially smaller wheel loads, foreign railroads use combined substructure layers 16 to 32 inches thick, with the smallest thickness corresponding to the highest quality subgrades (dense sand and gravel), and the largest thicknesses corresponding to the lowest quality subgrades (soft saturated clays). Thus, foreign railroads are providing greater substructure sections to handle lighter loads than applied on North American railroads.

Recent Substructure Analytic Developments - Several analytical computer models have been developed over the past 10 years that represent the individual track structure components. Models reviewed in this study are summarized in Table 4-7. The advantage of complex analytic tools such as these is their ability to represent the influence of different track structure component conditions economically. They can be used to perform parameter studies to determine the effects of changing load, rail, tie, ballast, subballast, and subgrade properties and geometry on the performance of other track components and on the track structure as a whole. The results of few parameter studies of this nature are available.

TABLE 4-6. TYPICAL FOREIGN SUBSTRUCTURE SECTIONS

Railroad	Static Wheel Load lbs.	Ballast Layer inches	Protective Layer inches	Stabilized Layer inches	Sealed Bitumen Layer inches	Concrete Slab inches	Total Thickness inches
Hungarian RR (MAV)	-	20	4 to 14(3)	(1)	(1)	-	24 to 34
Czech RR (CSD)	22,000						
Type 1 (2)		12	4 to 20(3)	-	-	-	16 to 32
Type 2		12	4 to 8	6 to 8	-	-	22 to 28
Type 3		12	4 to 8	-	4 to 6	-	20 to 26
Type 4		12	2 to 4	-	-	2.5	16.5 to 18.5
German RR (DB)	22,000	12	10 to 12(4)	10(5)			22 to 34

Japanese Nat. RR	19,800	CBR	Liquid Limit	Ballast	Slag	Crushed Stone	Sand Mat	Total
Sand I		2 to 4	-	10	6	10	-	26
Sand II		4 to 10	-	10	6	6	-	22
Sand III		10 to 20	-	10	6	0	-	16
Clay I		2 to 4	< 60	10	6	10	6	32
Clay II		4 to 10	> 60	10	6	6	6	28

Notes:

1. Hungarian Railway uses mechanical or cement stabilization, bitumen layers, and filter fabrics as required bv subgrade soil conditions.
2. Additional substructure specifications based on frost criteria.
3. Actual protective layer thickness selected based on deformation properties of subgrade.
4. For silty clay or clayey subgrades, 2.5 inch filter layer added to prevent mud pumping or fouling. Filter fabrics used also.
5. Cement stabilization used for low strength cohesive subgrades.

TABLE 4-7. ANALYTICAL MODELS DEVELOPED IN NORTH AMERICA

MODEL NAME	RESEARCHER(S)	MODEL DESCRIPTION	IMPORTANT FEATURES	REMARKS
Pyramid Model 1970	Meacham et al. (BCL)	Beam on elastic foundation analysis with modified track modulus, U	Used theoretical approach to determine U which included effects of rail type, tie type and width, tie bearing area, ballast type, depth and stiffness, and subgrade type and stiffness.	One of earliest attempts to rationally include the effects of substructure properties in track analysis. Poor correlation with field test results.
1970	Lundgren et al. (Illinois)	Two dimensional finite element model (FEM)	Analyzed longitudinal section along centerline of track. Plane strain behavior of substructure assumed.	Early forerunner of ILLITRACK. Poor correlation with measured results.
Analysis of Rail Track Structures (ARTS) 1978	Svec, Turcke, Raymond et al. (Queen's Univ.)	Three dimensional FEM. Beam elements for superstructure, hexahedronal and tetrahedronal elements for substructure.	Detailed description of physical track substructure. Stress path dependent and nonlinear elastic behavior of ballast, subballast, and subgrade accounted for using "bicubic spline" functions. No-tension capabilities of substructure materials accounted for.	Emphasized geotechnical aspects of track behavior. Bicubic spline functions developed from triaxial test data. Partially successful correlation with full-scale model data.
ILLI-TRACK 1976	Tayabji, Thompson and Robnett (Illinois)	Pseudo-three dimensional FEM. Two plane strain two dimensional FEM used in combination.	Element thickness increased with depth according to value ϕ in longitudinal analysis to represent transverse load spreading in plane strain analysis. Initial thickness of surface element made equal to effective tie bearing length, L to represent effective load transfer area between tie and ballast. Resilient modulus, E_r used to represent nonlinear elastic behavior of ballast, subballast, and subgrade.	Emphasizes geotechnical aspects of track behavior. Attempts to simplify and reduce costs of analytical models.
(PSA, BURMISTER) Track Structure Models 1975	So, Ho and Martin (AAR)	Series of 15 computer models to predict stresses and strains in various track components. Multiple models (simple and sophisticated) to perform same task.	Multiple models (simple and sophisticated) developed to perform same task. Model used depends on degree of analysis (preliminary or detailed). BURMISTER multi-layer elastic model developed for substructure. Prismatic Solid Analysis (PSA), a three dimensional FEM developed for superstructure analysis.	Computational requirements minimized for type of analysis needed. Component interactions may be lost through model subdivisions. PSA and Burmister model results agreed well with field data from others. Models used to perform parametric studies and develop sample design charts.
Multi Layer Track Analysis Model (MULTA) 1978	Prause, Kennedy et al. (BCL)	Combination of two models developed by AAR. The three dimensional FEM called LAC for superstructure analysis, and the Burmister multi-layer elastic substructure model.	Includes essentially all important aspects of individual track component performance in analysis. Interactive approach used between LAC and Burmister models to solve for stresses and strains in track structure components: ·Wheel-rail, rail-tie, and tie-ballast reactions are obtained from LAC. ·Influence coefficients generated by Burmister using uniformly loaded circular areas which represent the vertical pressure from equivalent tie bearing areas. ·Influence coefficients used in LAC to generate rail-tie reactions, rail-tie displacements, and tie-ballast pressures. ·Tie-ballast pressures used in Burmister to obtain stresses and displacements in substructure layers.	Allows the effects of changes in various track components on other components to be studied. No relative displacement between tie and ballast. Allows unrealistic tension to develop. Used homogeneous, isotropic, linearly elastic substructure properties. Substructure materials are nonlinear and stress dependent. Analytical results compared well with dynamic data from FAST.
GEOTRACK 1978	Adegoke, Chang and Selig (UMASS)	Modification of MULTA for studying substructure behavior.	Iterative procedure used to vary the resilient modulus, E_r, for the stress state in each layer. Stresses and E_r varied until a sufficiently converged solution is obtained.	Emphasizes geotechnical aspects of track behavior. Improved characterization of roadbed materials by including stress dependent, nonlinear behavior. Analytical results compared well with dynamic data from FAST. Uses truck loadings as opposed to axle loadings. Simplicity, efficiency, and cost improved from MULTA.

While the primary design criterion in track substructure design is to limit the vertical stresses on the subgrade to allowable levels, the ultimate design goal is to keep resilient and residual track displacements within tolerable limits. A method for predicting the residual deformation of the ballast has been developed by Selig et al.[11] This method is still in the preliminary stages of development, however, and must be extended to cover subballast and subgrade displacements. Field data are necessary to validate theoretical deformation predictions. The method proposed by Selig et al. predicts uniform total deformations; however, it is the differential settlement along the track that is of real interest to railroad engineers. With the accumulation of field total and differential settlement data, an empirical means of estimating differential settlement could be developed.

G. P. Raymond[12] has presented a rational, simplified design method for determining the required depth of ballast plus subballast over the subgrade. The method was developed within the framework of current North American design practice, modified using recent research findings, and updated for 100-ton car wheel loads. Subgrade allowable bearing pressures are a function of soil type. Bearing resistance can also be evaluated using the California Bearing Ratio (CBR) test or other test procedures. As such, it can be readily used by practicing engineers. The primary steps in the method are described below:

1. Determine the stress distribution with depth below the tie, using Boussinesq elastic theory, integrated for a rectangular, vertically loaded surface area. A uniform tie ballast contact pressure is used. Stresses from loads on adjacent ties on either side of the central tie are included.

2. From the allowable bearing pressure of the subgrade being considered, the stress distribution plot can be entered, and the required ballast plus subballast depth can be selected.

Raymond also outlined how to use the method to design for localized soft subgrades and to upgrade track to higher load levels. The method allows a relatively simple, yet rational, approach for analyzing track substructure conditions by modifying current AREA standard practice. Although the allowable subgrade pressures provided by Raymond appear reasonable for compacted subgrades, caution should be taken in applying them to unstabilized natural soils.

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[11]E. T. Selig et al., "A Theory for Track Maintenance Life Prediction, Second Year Final Report," prepared for U.S. Dept. of Transportation, Washington, D.C., December 1981, 160 pp.

[12]G. P. Raymond, "Design for Railroad Ballast and Subgrade Support," Journal of the Geotechnical Engineering Division, ASCE, Vol. 104, No. GT1, January 1978, pp. 45-60.

Design and Analysis for Lateral Loads

Proper horizontal alignment of railroad track is essential for maintaining a smooth ride, reducing wear on rail equipment, reducing track maintenance, and, most importantly, limiting train derailment. To maintain the horizontal alignment, the railroad track must have sufficient lateral strength to resist displacements caused by ther al loadings on unoccupied track and by the combined effects of thermal and wheel loadings on occupied track.

Resistance to lateral loads is provided by both the track superstructure and the substructure. The lateral bending stiffness of the rails and ties and the resistance of the fasteners to rotation about the vertical axis provide lateral track stiffness and strength. Lateral loads are transferred to the substructure through the ties embedded in the ballast. The forces applied by the superstructure are resisted by ballast/tie friction along the bottom and along two long sides of the tie and by a net passive pressure on the end-face of the tie. Lateral loads are transferred from the ballast bed to the subballast and then to the subgrade through shear stresses along the contacting surfaces.

The magnitude of lateral track resistance is controlled primarily by the nature of the tie-ballast interaction. Variations in track superstructure characteristics and subballast and subgrade properties have little influence on the observed magnitude of lateral track resistance. Ballast/tie resistance is caused by the frictional forces between the ballast and the tie bottom and between the ballast and the two long tie sides. Net ballast passive resistance is the force exerted by the ballast shoulder against the tie end-face when the tie is laterally displaced. Test results show that the contribution of the various resisting forces to the total lateral resistance is dramatically influenced by whether the track is unoccupied or occupied by a moving train. Research reported by others indicates that for unoccupied track, 50 percent to 60 percent of the total lateral resistance is derived from the frictional forces between the tie bottom and the ballast bed; 30 percent to 40 percent from passive end resistance; and 10 percent to 20 percent from frictional forces between the tie sides and the crib ballast. For occupied track, it appears that at least 95 percent of total lateral resistance is derived from the friction between the tie bottom and the ballast bed.

Current North American design practice for lateral loads, as given by AREA in its standard ballast sections, is to require full tie embedment and 6-inch ballast shoulders. AREA also presents a method for computing ballast shoulder width required to resist thermal loads.

A. D. Kerr[13] has developed a design aid for assessing safe temperature increases in continuous welded rail (CWR) on unoccupied track. As previously discussed, the French National Railway developed a method for determining the critical lateral force for occupied track subjected to vertical and lateral loadings. Mechanical ballast compaction has shown the potential to increase resistance to thermal buckling of CWR by 40 percent.

Field tests by Klugar[14], Riessberger[15], and Dogneton[16] indicated that increasing tie end area, by using "ear" ties, for instance, could increase passive end resistance by as much as 50 percent. Selection of other tie types such as "block" ties, tie reinforcements such as "safety caps", and improved CWR installation practices (better controlled track-laying temperature, less angular welds, less deformed rails) were also shown to increase lateral track resistance.

Design and Analysis for Longitudinal Loads

Longitudinal forces are developed in rails by train motion and by thermal effects. Resistance to longitudinal loads is controlled predominantly by the rail-tie fasteners and rail anchors, which restrict movements of the rail in relation to the ties, and by the ballast, which restricts movements of the ties. Without sufficient resistance to longitudinal loads, rail creep, skewing of ties, buckled track, or broken rail may result.

Literature surveyed for this study did not specifically address substructure design for longitudinal loadings. The following discussion is based on conclusions drawn from review of literature concerned primarily with lateral track resistance.

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[13]A. D. Kerr, Thermal Buckling of Straight Tracks; Fundamentals, Analyses, and Preventive Measures, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, Technical Report No. FRA/ORD-78/49, September 1978, 58 pp.

[14]K. Klugar, "Track Buckling Experiments of the Austrian Federal Railroads with New Types of Ties," Eisenbahningenieur (Railroad Engineer), Vol 25, No. 3, 1974, pp. 70-75.

[15]K. Riessberger, "Towards a More Stable Ballast Bed," Railway Gazette International, March 1977, pp. 99-102.

[16]P. Dogneton, "The Experimental Determination of the Axial and Lateral Track Ballast Resistance," Symposium of Railroad Track Mechanics and Technology, Princeton University, April 1975, A. D. Kerr, ed., Pergamon Press, New York, 1978, pp. 171-196.

The mechanism for resistance to longitudinal loadings is similar to that for lateral loadings. The magnitude of longitudinal track resistance is controlled by the nature of tie/ballast interaction. Subballast and subgrade properties have little influence on longitudinal resistance. Compared to the longitudinal direction, (1) the track superstructure is more flexible in the lateral direction, and (2) lower ballast resistance is provided in the lateral direction. Therefore, a ballast bed designed to resist lateral loadings is adequate to resist longitudinal loadings as well.

In contrast to track response to lateral loads, variations in superstructure characteristics--namely rail/tie fasteners and rail anchors--significantly influence the response of the track to longitudinal loads. Rail/tie fasteners and rail anchors are an essential part of the mechanism that transfers the longitudinal loads from the rail to the ties and the ballast bed. As for lateral resistance, the ballast provides resistance to longitudinal loads through ballast/tie friction and by passive resistance on the side of the tie. Passive ballast resistance develops along the long side of the tie, which is pushed into the ballast by the longitudinal forces. For a typical 7" x 9" x 8'6" wooden or monolithic concrete tie, the area available for development of passive resistance is more than ten times greater for longitudinal loadings than for lateral loadings. In addition, the crib ballast is confined in the longitudinal direction by the adjacent tie, increasing the longitudinal passive resistance.

Present North American design practices follow standards presented in the AREA Manual, modified by local experience. Appendix I of Chapter 5, Part 4, of the AREA Manual recommends that an optimum rail-laying temperature is within 10°F of the regional mean temperature. The intent of this specification is to limit thermally induced longitudinal and lateral buckling loads in CWR. In Chapter 5, Part 5, of the AREA Manual, specifications for numbers and locations of rail anchors are given. The intent of this section is to limit rail creep and tie skewing.

No studies of longitudinal loading have been located, probably because longitudinal problems can be remedied by installation of additional rail anchors. The rails are efficient in transferring longitudinal forces from tie to tie by axial rail stresses. Thus, the longitudinal force per tie can be reduced as much as necessary. Starting with the AREA Manual recommendations, rail anchors can be added until creep and skewing are negligible.

Drainage

Surface and groundwater runoff are the two major causes of track substructure problems. As such, design of systems to handle disposal of runoff is critical to successful track design. Drainage systems necessary to handle track surface runoff and subsurface drainage are generally those presented by AREA and are summarized in Section 3 of this report.

Evaluation Guidelines

Track substructure evaluation involves three steps:

1. Establishment of substructure performance criteria or standards.

2. Observation of track conditions.

3. Comparison of observations with performance criteria.

Substructure performance criteria should be based on the three basic functions of the track substructure: maintaining geometry, providing a resilient support layer, and providing rapid drainage. The purpose of track observation methods are to (1) identify safety-related track defects, (2) monitor general condition and changes in track conditions, (3) evaluate maximum service level of a track section, and (4) evaluate existing track performance in order to develop a design to upgrade performance.

Visual inspection is the most common observation method used today in North America; however, it is subjective and dependent on the experience of the observer. Track geometry cars are becoming more widely used to supply track geometry data. Lateral load tests have been used to evaluate the lateral resistance of track. Track modulus tests and various types of plate load tests have been used to measure substructure resilience, along with a dynamic system used on track geometry recorder cars.

No single method can satisfy the different requirements for or purposes of substructure evaluation. Several methods are presented, with the intent that each has its proper application. Further development and experience with these recommended methods are necessary before suggested guidelines for application can be developed.

4.2 LATERAL TIE PUSH TEST STUDY

Lateral Tie Push Tests--Data Analysis

A series of 76 single lateral tie push tests (SLTPT) were carried out in November 1979 by the DOT Transportation Systems Center, Cambridge, Massachusetts. The ties were situated on a portion of abandoned Amtrak main line track in Readville, Massachusetts, south of Boston.

The following factors were observed for most of the tests: tie general condition, tie surface roughness (top surface), ballast shoulder width, skew, tie dimensions, depth of crib, and lateral resistance versus displacement. The SLTPT device used was developed by Selig et al. as described in the 1977 report, "Field Methods for Ballast Physical State Measurement."

Ballast density was measured at five locations by water or sand displacement methods. The average measured density was 120 pcf. Ballast density was also measured at sixteen crib locations using backscatter readings from a nuclear density meter. The average density by nuclear measurements was 85.6 pcf. The discrepancy between the two measurement methods is judged to be due to difficulties in using a nuclear density meter on coarse materials. No analysis of the density data was attempted.

Lateral tie resistance was measured versus tie displacement. Two resistance parameters were analyzed--maximum resistance and the resistance at 4-mm displacement. The mean maximum resistance was 5253 pounds, with a standard deviation of 1027 pounds. The mean resistance at 4-mm displacement was 3418 pounds with a standard deviation of 755 pounds. The resistance at 4 mm displacement was used in all further analyses and correlations because the data were more consistent than the maximum resistance data.

Summary of Analyses - Attempts were made to correlate the various observed test parameters with the measured lateral resistance at 4-mm displacement. The following conclusions were reached:

1. The mean tie resistance increases with tie condition. That is, the mean resistance for good ties is greater than for fair ties and for fair ties is greater than for poor ties. However, the difference in resistance between ties of different condition is not significant in relation to the scatter (standard deviation) of the data. Tie condition was classified subjectively.

2. The relation between observed tie top surface roughness and resistance at 4 mm is uncertain. Medium-rough ties showed higher resistance than did either rough or smooth ties. Therefore, tie surface condition may have a limited influence on tie lateral resistance.

3. A direct correlation was observed between lateral tie resistance at 4 mm and tie volume, size, or weight. Linear regression analysis indicated that resistance increases 0.245 pounds for each increase of one cubic inch in nominal tie volume (nominal tie volume is the product of length times width times depth of tie). However, the correlation is of minor significance. The standard deviation of the data with respect to the regression line is only 4 percent less than the uncorrelated standard deviation.

4. A direct correlation was found between tie end area and lateral resistance. Linear regression analysis indicated a 40 pound increase in resistance for each square inch increase in tie end area. However, the correlation is of minor significance.

5. No significant correlation was discovered between tie length and lateral resistance.

6. Non-skewed ties showed 3 percent higher resistance than skewed ties. However, this difference is not judged to be significant.

7. An inverse relation between resistance and ballast shoulder width was determined. The resistance at 4-mm displacement decreased 63 pounds for each 1-inch increase in shoulder width. The correlation is judged to be low based on computed standard deviations. The limits of the slope of the regression line with 90-percent confidence are -14 to -111 pounds per inch. Therefore, the negative slope of the correlation would seem significant. This inverse relationship is not surprising because previous studies have shown that increases of shoulder width beyond 6 inches add little to the lateral tie resistance. The shoulder widths reported ranged from 7 inches to 29 inches. Further study of this conclusion is recommended.

8. Insufficient data on ballast density were obtained to determine a relation between resistance and density.

Conclusions - The following conclusions were based primarily on the evaluation of the 76 single lateral tie push tests carried out by the Transportation Systems Center at the Readville, Massachusetts site:

1. Due to the relatively large dispersion of the reported data, the significance level of the trends previously reported is relatively low. The track tested is old, so that the ties are probably of different ages. The maintenance practices along the length of the track (from tie to tie) may not be uniform. However, it is expected that sufficient traffic has traversed the track to dampen the influence of out-of-face maintenance. A review of the tie resistance measured versus location along the track does not reveal any consistent trend in the data.

2. The tie spacing (crib width) has been shown to be a significant factor in determining lateral tie resistance[17]. Measurements of tie spacing were not collected in this study. The variation of this factor is unknown, and the effect on lateral resistance in this test series cannot be evaluated.

3. Further study of lateral tie resistance is needed. Particular emphasis should be directed at the following:

a. Influence of shoulder width - The analysis of the data reported herein indicated a decrease in lateral resistance with increase in shoulder width. Further study of the importance of ballast shoulders to track lateral stability is desirable because shoulder width has an impact on track construction and maintenance costs.

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[17]Hofmann and Pfarrer, "Influence of Various Measures on the Lateral Displacement Resistance of the Unloaded Track," Report DT 44/D117/D, Office of Research and Tests, International Railway Union, 1976, p.30.

b. Influence of tie spacing - This factor has been inadequately studied.

c. Influence of ballast density - This factor has been inadequately studied; if nuclear density measurements are to be used, further study of the difficulties with this method will be necessary.

d. Comparison with panel pull tests - Evaluation of the panel pull tests also carried out at Readville, Massachusetts, may provide additional insight into the relation between single lateral tie push test results and lateral stability of the overall track.

4.3 ASSESSMENT OF DESIGN AND EVALUATION PRACTICES

The technology related to design and evaluation of railroad track substructures is not well developed, particularly in the United States. Design practices used today were generally developed from analytical, laboratory, and field studies performed over fifty years ago for track structures subjected to substantially smaller loads. Based on the largely empirical nature of these studies, their applicability to today's 100-ton and 125-ton car loads is questionable.

While more recent work has been performed in trying to develop track structure evaluation methods and guidelines, no clearly advantageous methods or guidelines have resulted.

Available design and evaluation methods which show promise for development of practical substructure design and evaluation are discussed below. Research necessary to develop these methods is outlined in Section 5.

General

As stated in Section 2.2, the most significant shortcoming in dealing with railroad substructure design and evaluation is the dearth of objective, in-service observations of the performance of track substructure systems and individual components. New or rehabilitated track design generally consists of selecting standard ballast and subballast thicknesses based on qualitative experience, without the benefit of quantitative in-service observations. The performance of new track substructure sections is rarely monitored on more than a qualitative basis. While two detailed monitoring programs have been recently performed, additional data are necessary for sites with different subgrade conditions and track substructures. Further details are provided in Section 2.2 and Section 5.

Track Loading Conditions

The static vertical loads imposed on the track are generally well defined. However, the effects of dynamic impact loadings and vibrations are not as well understood, and only recently have they come under closer scrutiny. Selig et al's.[18] data on the frequency and magnitude of dynamic impact loadings at FAST indicated that the dominant cyclic load frequency was due to truck loadings and not individual wheel loads. Spang[19] states that it is the high frequency vibrations induced in the track substructure that are the most important aspect of dynamic loading. Work done by the German Federal Railway seems to support this statement. A better understanding of the effects of vibrations on substructure performance is required, as are methods to insulate the track structure from damaging effects.

The magnitude of lateral and longitudinal loads transmitted to the substructure is poorly understood. While a better understanding of these magnitudes would be helpful, the present approach, used by foreign railroads, of measuring field performance of in-service tie and ballast components to develop a satisfactory system may prove sufficient.

Design and Analysis for Vertical Loading

Design methods currently available to North American railroads do not adequately include the effects of subgrade type and properties. G. P. Raymond[20] has recently taken a progressive first step toward modifying North American practice to include subgrade type and properties. The multi-layer elastic methods reported by the Japanese National Railways and several European railroads, and the effective stress approach reported by the Indian railroad are design methods that appear most favorable for use in upgrading current North American design practice. These methods incorporate subgrade types and properties and use field and laboratory testing methods to obtain the required subgrade data. In order to determine their applicability to North American practice, these methods should be used to design new track substructures. The in-service performance of these new structures should be observed and quantified in order to evaluate the effectiveness of the design methods.

The development of standard track sections with standard ballast and subballast sections is a reasonable design approach, provided that the development of sections is based on quantitative in-service observations of substructure performance. This will allow railroads to recognize when subgrade conditions are inappropriate for the use of standard sections. In such cases, validated design methods could be used to determine the required ballast and subballast thicknesses, or in worst cases, the necessary stabilization methods.

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[18]E. T. Selig et al., Status Report - Ballast Experiments, Intermediate (175 MGT) Substructure Stress and Strain Data prepared for U.S. Dept. of Transportation, Transportation Systems Center, Interim Report, September 1979, 88 pp.

[19]J. Spang, "Deformation of Railroad Track Base and its Stabilization," Eisenbahntechnische Rundschau, Vol. 21, No. 10, 1972, p. 376.

[20]G. P. Raymond, Op. Cit.

Analytical Computer Models - Analytical computer models, which can be used to perform parameter studies to determine the effects of changing load, rail, tie, ballast, subballast, and subgrade properties on the performance of other track components and the track structure as a whole, represent a potentially valuable tool for developing better substructure designs. Models that can perform these functions economically have been developed. The major obstacle to their use is lack of sufficient field measurement data to validate the accuracy of their predictions. Instrumentation and measurement methods necessary to obtain this field data are available, and programs to obtain field data for different subgrade and substructure conditions should be performed.

Track Settlement Prediction - The development of a method to predict total residual settlements of the various substructure layers is in the early stages of development. The method shows promise of developing a tool for economic planning of track maintenance life. An important step in obtaining a practical and useful tool will be developing a correlation between total settlements and differential settlements of the track substructure. Development of a field data base will be necessary to develop such a correlation.

Design and Analysis for Lateral Loads

No generally accepted analytical method, shown to be adequate with respect to substructure design for lateral loads, is available to the railroad industry. In general, standard designs are provided which, for the most part, appear to be based on qualitative experience. An increasing amount of research has been performed in recent years to evaluate these standard designs. The results of this work are briefly summarized as follows.

Ballast Bed Depth - A ballast section, level with the top of ties, provides optimum lateral resistance. This is the AREA-recommended practice, and no improvements or changes appear necessary.

Ballast Shoulder Width - The 6-inch-wide ballast shoulder recommended in Part 2 of the AREA Manual may or may not be sufficient to develop optimum lateral resistance. The use of a ballast shoulder wider than 6 inches has not been shown conclusively to improve lateral resistance. Ballast shoulders approximately 12 inches to 14 inches wide are presently used in Europe, where CWR is almost universal. Experts such as Kerr, 1978[21], have recommended

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[21] A. D. Kerr, Thermal Buckling of Straight Tracks; Fundamentals, Analyses, and Preventive Measures, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, Report No. FRA/ORD-78/49, September 1978, 58 pp.

the use of wider ballast shoulders in areas of North America where CWR is used. It is our opinion that the 12-inch to 14-inch ballast shoulder is warranted where CWR is used. A 6-inch shoulder is probably sufficient for jointed track. Shoulders wider than 12 inches probably add little to track lateral stability. A research program such as that carried out at FAST[22] should continue to evaluate the effectiveness of wide ballast shoulders in increasing lateral track resistance and to evaluate these recommendations.

Mechanical Ballast Compaction - After track maintenance activities, mechanical ballast compaction has been shown to improve lateral track resistance, to reduce differential settlement, and possibly to preclude reduced speed limits. Presently, ballast-consolidating machines, such as the Matisa D8 and the Plasser CPM 800, are commercially available. A study by Cunney, 1977[23], found that, "in the United States, the use of ballast-consolidating machines would be a valuable addition to track surfacing work in areas where CWR has a high probability of buckling under temperature stress after the ballast has been disturbed." Further studies should be initiated to determine areas where the use of mechanical ballast compaction is justified with regard to increased safety, and the economics of possible increased speed limits and decreased track maintenance.

CWR Installation Practice - The temperature at which CWR is laid relative to the highest and lowest expected local temperatures directly affects the induced thermal loadings and, consequently, the susceptibility of the track to thermal buckling and rail breaks. The general recommendation in the AREA Manual for rail-laying temperature within 10°F of the regional mean temperature is sufficient in areas where regional temperatures do not vary widely or where the consequences of track buckling or rail breaks are not severe. However, for critical applications (where the probability of thermal track buckling is high, and buckled or broken track could have disastrous effects) a more thorough investigation of the induced thermal loads and susceptibility of the track to thermal buckling should be made. In evaluating the probability of thermal track buckling, it appears that extensive work by Kerr has provided the best evaluation of thermal track buckling in unloaded track. His latest

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[22]"Ballast Shoulder Width Experiment," Technical Note FAST/TTC/TN-81/103, U.S. Dept. of Transportation, Facility for Accelerated Service Testing, Pueblo, Colorado, 1981, 15 pp.

[23]E. G. Cunney, J. T. May, and H. N. Jones, The Effects of Accelerated Ballast Consolidation, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, Report No. FRA/ORD-76/274, March 1977, 184 pp. (PB-266447).

publication[24] is a useful design aid for the practicing railroad engineer in evaluating safe temperature increases in unloaded track. In evaluating the behavior of loaded track to combined lateral and thermal loads, it appears that the empirical relationship developed by the French National Railways through extensive field testing provides a reasonably accurate relationship. As discussed by Prud'homme and Janin, 1969[25], and Kerr, 1978[26], lateral imperfections in track geometry, such as deformed rails or angular welds, will increase the susceptibility of CWR to thermal buckling and will cause difficulty in maintaining track alignment. If difficulty in maintaining the line is experienced, suspect rails should be changed and/or welds should be redone.

Tie Selection Criteria - The tie cross-sectional area, weight, and surface roughness can influence lateral track resistance significantly. Some criteria for the selection of ties relative to lateral track resistance should be included in the AREA Manual. Methods for improving lateral track resistance via the use of ties other than the standard AREA wooden ties or through "reinforcement" of ties are presently available. These include (a) the use of monolithic ties (wood or concrete) with a large cross-sectional area, (b) the use of discontinuous block-type concrete ties which, by the nature of their design, provide additional end bearing area, (c) the use of heavier ties (concrete or steel) rather than wooden ties, (d) the use of prototype-style concrete "ear ties" as employed by the Austrian Federal Railways, and (e) the use of "safety cap" reinforcement of ties, which has provided up to a 90-percent increase in lateral resistance on several European railroads.

Design and Analysis for Longitudinal Loads

Literature surveyed during the course of this study did not specifically address substructure design with respect to longitudinal loadings. As such, little seems to have been done to improve longitudinal loading design. This is probably due to the fact that none of the current major track structure deficiencies are attributed to stresses induced by longitudinal loads. In addition, those problems attributed to longitudinal loads, such as rail creep and tie skewing, are overcome relatively easily by installing additional rail anchors.

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[24] A. D. Kerr, Thermal Buckling of Straight Tracks; Fundamentals, Analyses, and Preventive Measures, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, Technical Report No. FRA/ORD-78/49, September 1978, 58 pp.

[25] M. A. Prud'homme and M. G. Janin, "The Stability of Tracks Laid with Long Welded Rails, Part I," Bulletin of the International Railway Congress Association, Vol. 46, No. 7-8, July-August 1969, pp. 459-487.

[26] A. D. Kerr, "Analysis of Thermal Buckling in the Lateral Plane," Acta Mechanica, Vol. 30, 1978, pp. 17-50.

Substructure Performance Criteria and Evaluation Methods

While track geometry criteria provide data on overall track performance, they do not provide insight into the performance of track substructure components. Much work needs to be done before realistic substructure performance criteria and evaluation methods can be established. The most fundamental requirement is the development of an extensive data base obtained by measuring the performance of track substructure components under various in-service conditions. With the improved understanding of substructure behavior obtained through such a data base, performance criteria and evaluation methods can be developed.

5. TRACK SUBSTRUCTURE RESEARCH REQUIREMENTS

The goals of the Railroad Ballast and Subgrade Requirements Study were as follows:

a. Develop guidelines for selection and use of materials in track substructure

b. Develop guidelines for evaluation of track subgrades and implementation of stabilization procedures to upgrade subgrade performance

c. Develop guidelines for design and evaluation of track substructures.

Some suggested practices have been set forth in the interim reports to achieve these goals; however, available technology is developed insufficiently to complete guidelines for these areas based on experience and observations of track. This section identifies the areas of future research needed to develop the guidelines.

The results of several recent studies have been published that identify research needs related to rail transport. The Railroad Research Study, published in 1977, examined the broad spectrum of needs of the railroads[1]. Permanent way (track structure and substructure) was only a minor factor discussed in this study[2].

A study more pertinent to the present topic was carried out by the MITRE Corporation for the Federal Railroad Administration[3]. Two planning studies were performed that identified the most critical track system rehabilitation and maintenance problems. Tables 5-1 and 5-2 list the rank-ordered problems identified in the study. Only those problems associated with the substructure elements are listed. The problems omitted are related to track superstructure elements.

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[1]Rail Transport Research Needs, Final Report of the Railroad Research Study, Conducted by the Transporation Research Board, Sponsored by the U.S. Dept. of Transportation, Federal Railroad Administration and the Association of American Railroads, Special Report 174, Transportation Research Board, Washington, D.C. 1977, 77 pp.

[2]Ibid, pp. 48-49, p. 65.

[3]M.J. Zobrak, Track Rehabilitation and Maintenance Research Requirements, Report No. FRA/OR&D-80/09, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, 1980, 68 pp.

While there are similarities evident in Table 5-1 and 5-2, it is also clear that emphasis of certain aspects of track performance is variable. These differences are brought about by the individual perceptions recorded by the two survey teams which approached separate segments of the railroad community.

TABLE 5-1. RANK-ORDERED TRACK SYSTEM PROBLEMS--MITRE CORP. STUDY[1]

Rank*	Problems
1	Inadequate Track Structure Cost/Performance Data
3	Insufficient Cost/Performance Information on Ballast
4	Excessive Longitudinal Rail Stress
10	Insufficient Information about Subgrade Performance
12	Unknown Cost/Performance of Subgrade Improvement Methods
15	Inadequate Methods for Subgrade Improvement
16	Excessive Ballast Degradation
17	Excessive Ballast/Subgrade Interactions (Pumping)
30	Track Geometry Problems
34	Inadequate Subgrade Assessment Techniques
37	Excessive Ballast Fouling
38	Inadequate Slope Stabilization Methods
39	Insufficient Information on the Causes of Railway Accidents
41	Inadequate Ballast Maintenance/Rehabilitation Methods
42	Inadequate MOW Methods at Crossings
45	Subgrade Heaving
47	Inadequate Methods for Evaluating In-Situ Track
48	Unknown Cost/Performance of Concrete Tie Fasteners

*The rank numbers indicate order of importance. The numbers missing are problem items unrelated to substructure, such as rail metallurgy and train operations.

[1]M.J. Zobrak, Track Rehabilitation and Maintenance Research Requirements, Report No. FRA/OR&D-80/09, prepared for U.S. Dept. of Transportation, Federal Railroad Administration, 1980, 68 pp.

TABLE 5-2. RANK-ORDERED TRACK SYSTEM PROBLEMS--PBQ&D[4] STUDY

Rank	Problems
4	Insufficient Cost/Performance Information on Ballast
8	Unknown Cost/Performance of Subgrade Improvement Methods
9	Inadequate Methods for Subgrade Improvement
11	Inadequate Track Geometry Measuring Methods
13	Inadequate Track Structure Cost/Performance Data
15	Excessive Ballast/Subgrade Interactions (Pumping)
20	Inadequate Maintenance of Way Methods
25	Inadequate Methods of Tunnel Drainage
31	Excessive Ballast Fouling
32	Inadequate Subgrade Assessment Techniques
33	Insufficient Track Availability for Maintenance
38	Excessive Ballast Degradation
55	Insufficient Information about Subgrade Performance
56	Inadequate Slope Stabilization Methods
59	Inadequate Protection from Blowing Soil

5.1 SUBSTRUCTURE MATERIALS RESEARCH REQUIREMENTS

The following subsection presents the most critical problems identified in this study of railroad substructure engineering that must be solved to realize some of the goals related to substructure materials selection, subgrade stabilization, and substructure design and evaluation.

Ballast Material Selection

The currently available specifications for ballast are of only limited usefulness in the selection of ballast materials. The specification limits, such as stated in the AREA Manual, are judged to be too lenient to eliminate all low performance materials. In addition, they provide no real guidance on the comparative rating of different materials.

[4] PBQ&D = Parsons, Brinckerhoff, Quade & Douglas.
R.H. Wengenroth and H.P. Clapp, "Track and Bridge Maintenance Requirements," U.S. Dept. of Transportation, Federal Railroad Administration, Washington DC, March 1980, FRA/ORD-80/11, PB 80-207855.

The principal research needed in the area of ballast technology is collection of field performance and laboratory property data on different ballasts under different conditions--loads, environments, tie types, subgrade and groundwater conditions, and other factors. It is important to observe the performance of different materials in the same application and the same material in different applications. The field observations described in 1976 by Gaskin and Raymond in "Contribution to Selection of Railroad Ballast" form the initial basis of an objective-subjective field performance rating system. These types of observations should be combined with the procedures recommended in the Earth Materials Practices[5] report for testing of in-service ballast.

Field observations of material performance should be combined with observations of overall track mechanical performance as described below. After all, the ability of the substructure to limit long-term track displacements and provide suitable track resilience is the bottom-line measure of substructure performance. Material performance cannot be judged independent of these factors.

In conjunction with the field observations, laboratory testing following the recommendations of Table 2-3 should be carried out. These data will form the basis of correlations between index characteristics and observed field performance.

The result of the analyses of all these data should serve as a guide to comparative rating of ballast materials. The significance of different factors and index characteristics should be identified. The influence of factors such as freeze-thaw resistance, effect of contaminants such as locomotive sand, and tie-ballast pressure should be identified so that desirable properties of ballast in different applications can be evaluated.

Ballast Gradation

There are differences of opinion concerning optimal gradation of ballast. Many railroad engineers prefer the coarsest, most uniformly graded ballast they can obtain to provide high lateral resistance and ample voids for accepting ballast contaminants. Recent research by Raymond and others suggests that more broadly graded materials may provide greater benefits in terms of limiting residual vertical strains and isolating the ballast from external contamination from either above or below the ballast bed. However, this proposal for ballast gradation requires testing in service track.

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[5]R. M. Simon et al., "Ballast and Subgrade Requirements Study: Railroad Track Substructure - Materials Evaluation and Stabilization Practices," U.S. Dept. of Transportation, Federal Railroad Administration, Washington DC, 1983, FRA/ORD-83/04.1, pp. 113-115.

External Ballast Fouling

Contamination of ballast by materials blown, dropped, or washed into the ballast bed may not be completely controlled by the ballast material. Studies are needed to develop methods to control external fouling. The following areas should be explored:

a. Stabilization of soils adjacent to track to resist wind erosion.

b. Quantitative evaluation of the effectiveness of different methods of ballast cleaning--shoulder cleaning, crib cleaning, undercutting.

c. Effect of ballast gradation on movement of external contaminants; one advantage of broadly graded ballast is that it may limit movement of particles through the ballast bed. However, this hypothesis has not been proven by field experience.

5.2 SUBGRADE STABILIZATION RESEARCH REQUIREMENTS

Many of the subgrade stabilization methods described in the first interim report have never been applied to railroad track problems. As such, these would need careful evaluation both during the design phase and after construction by observations of performance in the field. Several methods of subgrade stabilization have grown in popularity with the railroads in the past several years. However, some uncertainties remain in the application and design of these methods of stabilization that should be addressed by future research studies as outlined below.

Lime Slurry Pressure Injection

Lime slurry pressure injection (LSPI) has grown increasingly popular as a method to stabilize soft clay subgrades. Yet, as suggested in the stabilization practices report, there is little rational basis to explain the improvements in subgrade properties. Performance improvement after LSPI has been erratic. The following research needs have been identified:

a. Develop a rational basis to explain improvement brought about by LSPI. This should include excavations of sites where LSPI has been successful as well as unsuccessful. Factors to be investigated include distribution of lime within the soil mass and change of soil properties and chemistry caused by LSPI. Effects of LSPI on ballast, subballast, and subgrade should be distinguished.

b. Develop guidelines for application of LSPI to subgrade deficiencies. These should include (1) procedures to identify where LSPI will be effective, (2) factors to be considered during field injection, and (3) related factors, such as drainage, that should be considered in design of the rehabilitation program to improve probability of successful stabilization.

Filter Fabric

Several studies are underway to evaluate filter fabric installations on operating railroads. Considering the improvement in subgrade performance that has reportedly been realized by installation of filter fabric, these studies should be pursued and expanded. Factors to be established are (1) optimal fabric properties for railroad applications; (2) installation procedures, particularly depth of ballast and/or subballast between ties and fabric; (3) identification of optimal position for fabric insert--bottom of ballast or within or below subballast; (4) life of material in track; (5) associated improvements, such as drainage, that should accompany fabric installation; and (6) quantification of improvement in substructure performance produced by fabric installation.

Drainage

Procedures for designing drainage structures are well established. Yet design criteria that specify required drainage performance for specific subgrade and environmental conditions are not available generally. Effects of drainage parameters on development of mud pumping, frost action, and other subgrade problems should be studied in order to refine design criteria guidelines.

Ballast Pocket Grouting

Grouting of ballast pockets received wide application twenty to thirty years ago, yet has fallen into disfavor in recent years. No definitive reports were located to explain the fall from popularity. Interviews with railroad engineers indicate that ballast pocket grouting caused general cementing of the ballast, interfering with future ballast maintenance. These tentative conclusions should be confirmed or denied. It may be possible to develop a grouting procedure that permits stabilization of the ballast pockets, yet avoids general cementing of the ballast, loss of resilience, and maintenance problems. As a nondisruptive method of treating a prevalent subgrade problem, grouting would be attractive if some of the problems with the method can be worked out.

5.3 SUBSTRUCTURE DESIGN RESEARCH REQUIREMENTS

Several methods of track substructure design developed for foreign railroad engineering practice were described in the Design Practices report[6]. These methods provide a rational basis for adjusting the substructure thickness to account for subgrade properties. Several complex analytic treatments of railroad track using computer programs are available. Optimal application of these powerful analytic tools is yet to be realized. Specific recommendations follow.

Track Design Methods

The several closed-form methods for analyzing substructure thickness, such as those prepared by JNR, the Indian State Railway, and by G. P. Raymond, are judged suitable for routine track design. The different methods recommend different or several optional means to measure subgrade properties for the analysis. None of these available methods and options have been systematically evaluated and compared in practice. Research programs should be based on several sections of in-service track, including the necessary subgrade soil property tests, such as CBR, plate load, vane shear, and cone penetrometer tests, and measurements of track performance. Different types of subgrade, groundwater, loading, and geometry conditions should be explored. Based on evaluations of the performance of track built according to the different design methods, it should be possible to develop tentative design guidelines based on actual in-service experience.

Vibrations

Design of track substructures with respect to high frequency vibrations has not been adequately addressed. A research program should be performed expanding on work previously performed by the German Federal Railway and others. This work should center on reducing the vibration energy delivered to the substructure by developing better insulating materials.

Computer Analytic Models

The several available computer analytic models summarized in Table 4-7 have been compared by Chang et al.[7]. The selection of the GEOTRACK program

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[6]M. A. DiPilato, et al., "Ballast and Subgrade Requirements Study: Railroad Track Substructure - Design and Performance Evaluation Practices," U.S. Dept. of Transportation, Federal Railroad Administration, Washington DC, 1983, FRA/ORD-83/04.2, pp. 60-74.

[7]C. S. Chang et al., "A Study of Analytical Models for Track Support Systems," prepared for the TRB Annual Meeting, January 1979.

as an accurate and practical method of track analysis is a reasonable judgment in our opinion. However, the accuracy of the model should be confirmed by testing, analysis, and field observations at track sites other than FAST in order to vary subgrade type. Different types of subgrade conditions should be investigated.

The principal value of computer models is their economy in performing parameter or sensitivity studies. Using an adequately validated model, these types of studies will provide insight into the substructure performance benefits to be derived by increasing ballast thickness, tie spacing, and other substructure parameters. Few such studies exist presently.

Track Displacement, Track Geometry, and Maintenance Life Predictions

Conventional procedures for analysis and design of track substructures are based on calculations of peak stresses and resilient displacements induced in the substructure by train loads. The procedure developed by Selig et al.[8] to predict maintenance life of track is based on calculations of the average residual compression of the substructure.

On the other hand, criteria that affect the operation of trains are related to differential track displacements--alignment, surface, cross-level, and twist. With the exception of some data collected at FAST, there are no known data that compare the differential track displacements, such as are derived from track geometry car measurements, to measurements of total track displacement as might be derived from field survey observations.

If the basis of track design is calculation of total stresses and displacements, a correlation must be developed between total average displacements and track geometry criteria that control train operations. These correlations should be based on programs of field observations of in-service track performance. The first phase of this observation program should be establishment of a track geometry quality index to be used in the program as discussed below under substructure evaluation.

5.4 SUBSTRUCTURE EVALUATION RESEARCH REQUIREMENTS

The principal functions of the track substructure are to maintain track geometry, vertically and laterally, and to provide resilience to dampen dynamic forces induced by trains. Further development of substructure evaluation methods and criteria for all these factors is needed as described below.

[8] E.T. Selig et al., "A Theory for Track Maintenance Life Prediction, Second Year Final Report," U.S. Dept . of Transportation, Research and Special Programs Administration, Washington, D.C., June 1981, DOT/RSPA/DPB-50/81/25, 178 pp.

Geometry Indices

The track geometry car is an important tool in evaluating the consequences of substructure performance. A principal substructure function is to limit track differential displacements. The major shortcoming in application of geometry cars is in interpretation of the data. The various geometry cars manufactured differ in some of the details of the actual measurements made. Additionally, there are several methods of combining the individual track geometry parameters into a geometry quality index. Study is needed to evaluate the relative advantages of the different measuring systems and the relative significance of the different track quality indices to represent geometry and substructure performance as it affects train operations.

Vertical Resilience

Measurements of vertical resilience were carried out sixty and more years ago to determine the track modulus for the beam-on-elastic-foundation calculations. Studies of the standard methods of measuring vertical resilience, as well as of some novel techniques, are desirable as described below.

Track Modulus Test - The track modulus test is based on the theory of beams-on-elastic-foundations. Typically, a locomotive or car is used to provide the load on the rail. Measurements of track displacement may be made at a single location, or the longitudinal distribution of track displacements under load may be measured. The analytic equations are used to derive the track modulus from the displacements. Sometimes, single ties are loaded and analyzed. The test is judged to be useful in that it applies a prototype static load to the substructure in-situ, and minimal disruption of the track is required.

Factors that require further development are (1) a recommended method of making measurements and reducing the data, (2) use of the data in substructure evaluation, and (3) development of performance criteria.

Plate Load Tests (PLT) - The PLT is the standard test for evaluation of rigid pavement subgrades. Selig[9] has proposed using a 5.5-inch-diameter plate loading test to evaluate ballast physical state and to measure performance of other substructure elements. This proposal is judged to have merit. Study of the PLT as a means to evaluate track substructures should be combined with the program discussed earlier to study use of the PLT to provide parameters for track analysis and design.

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[9] E.T. Selig et al., "Field Methods for Ballast Physical State Measurements," Mechanics of Ballast Compaction Study, prepared for U.S. Dept. of Transportation, Transportation Systems Center, November 1977, pp. 17-25, 71-95.

Vibroseismic Survey - The vibroseismic survey and other geophysical means of testing track substructure, such as seismic refraction survey and subsurface radar, should be investigated as to their value and application to evaluating track substructures.

Lateral Resistance

Lateral resistance of track to restrain buckling has become critical as continuous welded rail has replaced jointed rail. The following factors require study:

a. Required lateral resistance to restrain buckling. Kerr (1978) has developed a buckling model that requires critical evaluation and perhaps modification.

b. Factors affecting lateral resistance. These were discussed in the design and evaluation practices report[10], as well as in the analysis of the single lateral tie push tests conducted at Readville, Massachusetts, and analyzed for this study[11]. Further studies are recommended, both in laboratory prototypes and in the field, to help define the critical factors affecting lateral resistance. Field tests should be carried out on sections of well-maintained and poorly performing track.

c. A suitable method of evaluating lateral resistance should be devised.

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[10] M. A. DiPilato et al., Op. Cit., pp. 18-21, 93-118.

[11] "Single Lateral Tie Push Tests, Readville, Massachusetts, Data Analysis," prepared for U.S. Dept. of Transportation, Transportation Systems Center, December 1980, 111 pp. (unpublished, Contract DOT-TSC-1527).

APPENDIX A

REPORT OF NEW TECHNOLOGY

The findings of this study are based on a review of published literature, discussions with practicing engineers, and our own experience. As such, no novel technologies have been developed.

The purpose of the first portion of this study is to determine the state-of-the-art of earth materials practices as they may be applied to railroad substructure engineering and subgrade stabilization. The technology of railroad engineering, pavement engineering, geology, and soil mechanics were drawn on to develop recommended materials practices for dealing with track substructures. Thus, it is proposed to apply existing technologies to new uses. Recommendations for applying standard soil testing procedures to classifying and characterizing subgrade soils is contained in Table 2-2. Recommendations for classifying and characterizing ballast materials are contained in Table 2-3.

The second segment of the study surveyed a broad selection of subgrade stabilization methods. These methods have been evaluated with respect to their application to railroad substructure engineering, in particular, non-disruptive improvements to track subgrades. Application of stabilization methods is summarized in Tables 3-1 and 3-2.

The final phase of the study reviewed the practice of track substructure design, as followed in the United States, as well as the theoretical design basis. Substructure design procedures used by European and some other foreign railroads were described. Application of these procedures to U.S. railroads would represent extension of existing technology to new applications--in particular, to design for heavy axle loads on standard gauge track.

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