Subgrade and Ballast Requirements for 125-Ton Cars

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The main points relating to the performance of railway track subgrades are outlined. Particular consideration is given to the effect of increasing axle loads from 30 tonnes, standard on 100-ton cars, to 36 tonnes, estimated as probable for 125-ton cars. Two aspects are discussed, new track construction and upgrading existing track. On existing construction, where subgrade stability is borderline, an appropriate ballast lift to maintain or increase the existing factor of safety may be determined. For new construction, various aspects of subgrade preparation are briefly reviewed. These include the importance of adequate compaction, the treatment of subgrade soils with cement, and the treatment of subgrade soils with lime. Special aspects of dealing with swelling soils or high-sulfate soils, where avoidance is uneconomic, are also mentioned. Drainage and subballast use and requirements are also stressed. For existing track on chronically unstable clay subgrades or unstable embankments, consideration should be given to cement or lime slurry pressure injection. Slurry techniques are best performed by a specialist contractor who has had extensive experience with the technique. New conclusions are stated for many of the aspects reviewed, and often neglected aspects of subgrade and subballast requirements are highlighted.

The two main requirements of a stable subgrade are (*a*) the provision of sufficient granular or modified soil cover to ensure that overstressing does not occur and (*b*) the provision of a granular filter blanket to prevent piping and thus loss of subgrade fines from below the track load-bearing area. To ensure that overstressing does not occur, track stresses need to be calculated. The writer (*1*) has previously recommended a means of calculating these stresses. The method is used in an example of upgrading of tracks that carry 100-ton cars so they can carry 125-ton cars. When fully loaded, a 100-ton car typically has 30-tonne axles and a 125-ton car has 36-tonne axles. These axle loadings will be assumed herein.

By using the approach previously outlined by the writer, the stresses in any direction at any point may be calculated for any load configuration. As an example of solutions obtainable with the method, Figure 1 shows the calculated vertical stresses below an interior axle of a configuration of two stationary coupled G-75 trucks for 30-tonne and 36-tonne axle loading and two postulated conditions: (*a*) on track that has a modulus of 14 MN/m/m of rail constructed with 229-mm crossties at 459 mm center to center and 68-kg/m rail representing the most conservative North American main-line wood crosstie track and (*b*) on similar track that has a modulus of 224 MN/m/m of rail constructed with 279-mm crossties at 610 mm center to center representing North American concrete crosstie track with stiff tie pads.

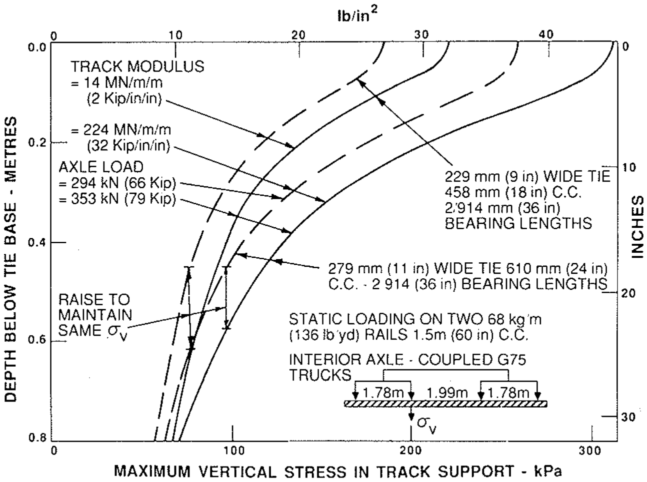

FIGURE 1 Variation of maximum vertical stress through the soil profile below two extreme examples of typical North American track from the inboard axle of two coupled G-75 trucks with static 30- or 36-tonne axle loadings showing the increased ballast cover to maintain subgrade stresses.

If only static axle loads are considered, the results in Figure 1 may be compared to obtain the increased ballast depth required to maintain at least the same subgrade factor of safety when axle loads are increased from 30 tonnes to 36 tonnes. Such a comparison is shown for an assumed granular cover of 0.45 m in a track that takes 30-tonne axles. Dimensioned is the increase in cover required to maintain the same vertical stress should the axle loads be increased to 36 tonnes.

Similar calculations have been performed for the same two track configurations but for different track moduli. Figure 2 shows the results obtained, using different moduli between 3.5 and 224 MN/m/m of rail, for initial ballast covers above the subgrade of 300, 500, and 700 mm. It is apparent from Figure 2 that the initial track modulus has less influence than does the initial cover on the increase in cover required to maintain the same vertical stress at the subgrade elevation. Indeed, a large variation in the assumed track modulus has little effect on the results unless it is initially quite stiff. These results confirm the general practice of assuming values of track moduli rather than using accurate measurements. In

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addition, the track modulus is likely to vary with the seasons and along any length of track. Of course, Figure 2 applies only to the upgrading of existing track. In any application in which the track modulus is physically changed, such as when wood ties are replaced by concrete ties, the subgrade stresses will also be changed. This is clearly seen in Figure 1 by comparing the vertical stress profiles for the two different constructions. It also shows why most railways upgrade and place new and more ballast below the ties when replacing wood ties with concrete ties.

It should be clearly understood that Figure 2 deals with the increase in cover required on subgrades stable under 30-tonne axles that are to be maintained at the same factor of safety or better under 36-tonne axles. Of course, many subgrades may have high factors of safety under 30-tonne axles, and these may still be at an acceptable level under 36-tonne axles even without any ballast raise. The major point is that, based on static loading, Figure 2 shows the increases of ballast that may be considered the maximum requirement when safety factors against subgrade failure are considered at their desired limiting values.

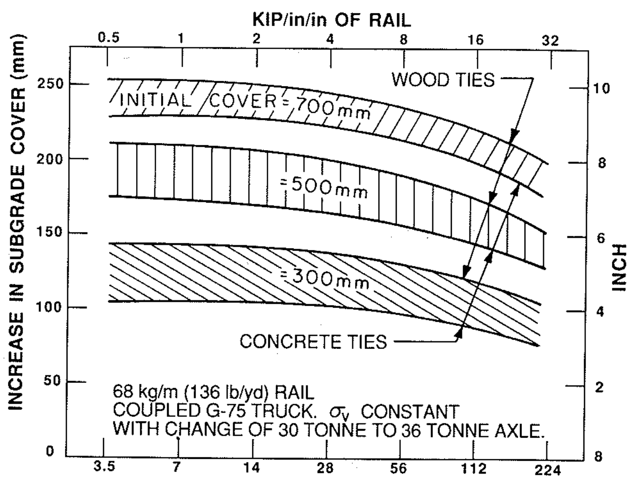


FIGURE 2 Values of increased ballast cover required to maintain subgrade stresses from 36-tonne axle loadings at the same values as those from 30-tonne axle loadings, obtained from plots similar to those shown in Figure 1.

DYNAMIC LOADING

The writer (*1*) also presented information indicating that track irregularities or wheel irregularities, or both, are the principal cause of major dynamic track forces at present-day (1987) speeds. An approximation for the dynamic increment was given (*1*).

Subsequent calibration of this expression for speeds greater than 75 km/hr has resulted in the empirical solution

$$\Delta P_d = 4.3 s M^{0.5} U^{0.375} V \tag{1}$$

where

ΔP_d = dynamic increment in N,
s = depth of the irregularity in mm,
M = unsprung mass in kg,
U = track modulus in MN/m/m of rail, and
V = vehicle speed in km/hr above 75 km/hr.

Because Equation 1 is an empirical equation, the units of measurement of each parameter must be strictly maintained.

Unless the unsprung mass or track quality is changed, Equation 1 states that the dynamic loading increment would be the same for 36-tonne axles as for 30-tonne axles. This is particularly true for those railways that overload 100-ton cars to produce 20 percent additional axle loading. Typical solutions for a 100-ton car, obtained for the two conditions cited for Figure 1 plus an intermediate condition, are shown in Figure 3. These results assume the rather severe case of a 51-mm² flat on an inboard axle and thus emphasize that vertical stress is greatest near the tie base level. Thus the values given in Figure 2 will be conservative when static plus dynamic loading is evaluated. The increased static loading from the heavier axles could, of course, be sufficient to cause track or wheel defects to occur quite rapidly, which would result in uneconomical maintenance, particularly if track and wheel quality were to remain unchanged.

Acceptance of Equation 1 as valid means that the conclusion related to the depth increment already expressed for static loading is valid for static plus dynamic loading unless track or wheel defects are permitted to increase. That is, the increased cover shown in Figure 2 should maintain the subgrade stresses below 36-tonne axles at values less than or equal to those existing below 30-tonne axles. Equation 1 also states that dynamic loading of the subgrade may be reduced by decreasing the track modulus. This means using greater depths of clean granular ballast and subballast and softer tie pads with concrete ties.

BALLAST DEPTH DESIGN

Clearly evident from Figure 3 and Equation 1 is the dramatic effect a higher track modulus has on the dynamic increment.

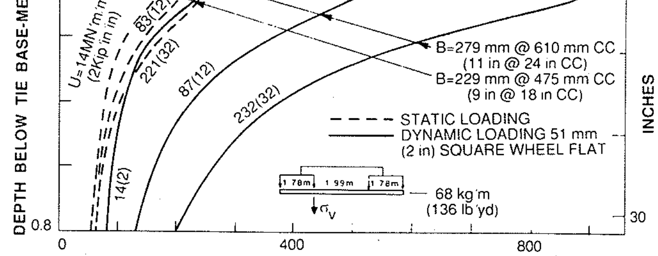


FIGURE 3 Variation of maximum vertical stress through the soil profile below three examples of typical North American track from an inboard axle of two coupled G-75 trucks with 30-tonne static axle loadings and static loading plus dynamic loading from a 51-mm² wheel flat on the axle wheels of the inboard axle traveling at 80 km/hr.

This has recently been confirmed by Scott (*2*) in research designed to establish loading on concrete turnout ties. As pointed out by the writer (*1*), it is fortunate that such moduli are generally associated with firmer, and thus generally stronger, subgrades. The stiffer concrete tie track results in more resistance to the formation of large track irregularities leaving wheel irregularities as the predominant concern related to dynamic increment on continuously welded rail. Fortunately, wheels do not generally have carefully made square flats associated with "worst conditions," and flats are associated with a small percentage of wheels. Typical foundation design is based on the dead load plus some percentage (often 50 percent) of the maximum live load. This is acceptable because established safe soil load-bearing stresses generally include some measure of safety factor that may be exceeded on a limited basis. They are also generally based on repetitive loading under soaked subgrade conditions.

When a design live load has been selected, the calculated stresses may be obtained for any loading including 125-ton cars. These stresses are then related to safe soil load-bearing stress (*3*), such as those shown in Figure 4, or other available soils data to obtain the required granular (subballast plus ballast) design depth. As pointed out elsewhere (*1*), Figure 4 was developed for use in highway and airport design, and the limits are considered conservative for use in track support subgrade design. A 50 percent increase was suggested (*1*).

Where climatic conditions result in freezing temperatures, a minimum granular cover equal to at least one-half the depth of frost penetration is generally specified.

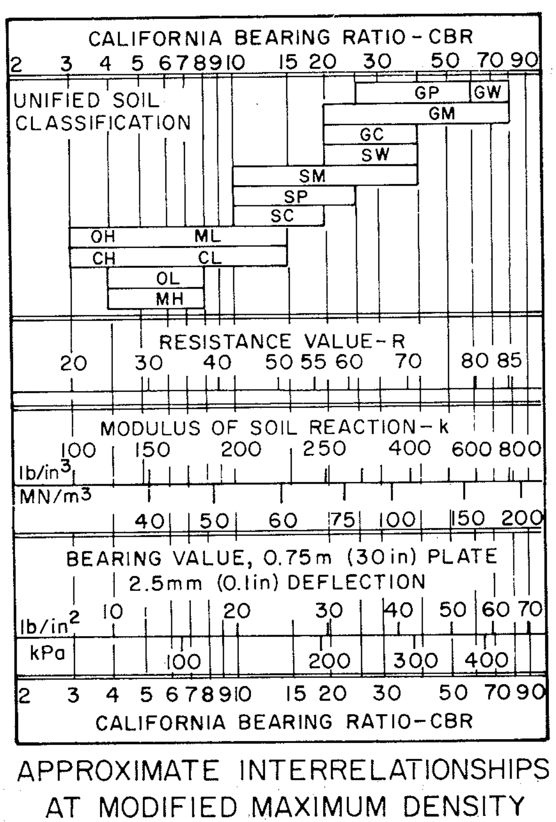


FIGURE 4 Safe soil load-bearing stresses developed for highway and airport design (*3*).

EQUIVALENT DAILY LOADING AND EQUIVALENT GRANULAR COVER

In highway design it is normal practice to account for the variety of axle loadings that traverses any given point. In railway operations it is most economical to load axles to maximum permissible values. Thus equivalent axle counts are not a consideration in railway design. Furthermore, axle loadings are not decreased seasonally. As demonstrated by Heath et al. (*4*), fatigue failure in subgrades occurs fairly rapidly when threshold stresses are exceeded. They also showed that loadings near but below the threshold stress caused little damage. Thus failure is quite sensitive to small increases when stresses are near the threshold but insensitive to large changes as long as the threshold stress is not exceeded. Such findings are in agreement with those of Raymond et al. (*5*) and Gaskin et al. (*6*). Equivalent daily loading considerations are thus not generally required for track design.

Another factor that is sometimes considered in highway engineering is the granular equivalency factor. This is shown in Figure 5, which has been taken from research by Herner (*7*). Because ballast has a very open structure and, even when properly protected from subgrade fouling, is subject to fouling by windblown and other debris, it is doubtful that equivalency factors should be assigned to aggregates used to protect the subgrade.

SUBGRADE TREATMENT

On new construction designed to minimize future maintenance, whether for 125-ton cars or lighter vehicles, it is normal practice to remove topsoil for further use and proof-roll the surface of the subgrade excavation to locate unacceptable weak zones, particularly in cuts and low fills. Weak zones are generally subject to further excavation

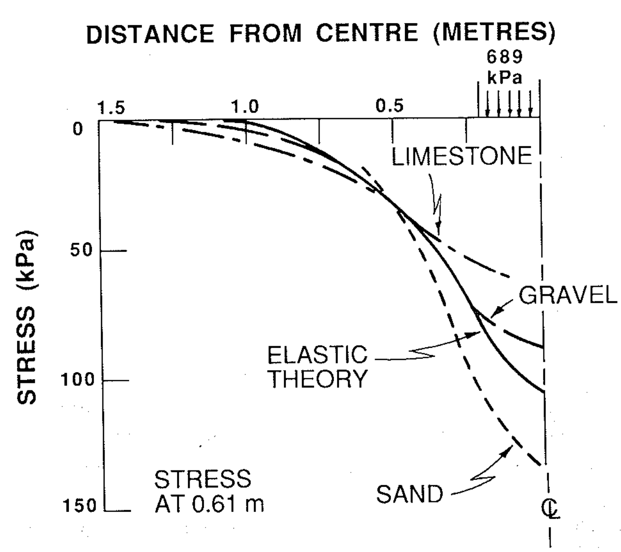


FIGURE 5 Vertical stresses measured by Herner (*7*) at a depth of 610 mm below loaded aircraft wheel on different types of granular soil support.

followed by compaction of any replaced soil. Acceptable areas are often scarified, after the addition of any water necessary to achieve optimum, to a depth of about 0.15 m and recompacted to 90 percent of maximum density as defined by ASTM D 1557 or 95 percent of maximum density as defined by ASTM D 698. Even when these precautions have been taken, the compacted, soaked subgrade strength may be sufficiently weak that granular cover requirements exceed the minimum depth on new construction of 305 mm (12 in.) of ballast plus 150 mm (6 in.) of subballast recommended in the *Manual for Railway Engineering* (*8*, Article 1.2.5.4). Where granular materials are scarce, such as in midwestern North America, a makeup depth of the subgrade may be treated with lime, flyash, cement, or other suitable additives to produce a stronger upper crust of treated subgrade to replace part of the granular cover requirement.

The treated subgrade is generally regarded as equivalent to unbound granular material. This is because the modified soil layer is generally quite brittle and would crack under loading. For example, the maximum calculated tensile stress using theoretical solutions developed by Burmister (*9*) at the bottom of the second layer of a three-layer elastic solid is shown in Figure 6. It is therefore essential that such modified layers be covered with a noncementing and thus a nonplastic granular material. Such granular material must be graded to act as a filter to the subgrade and be located immediately above the modified soil.

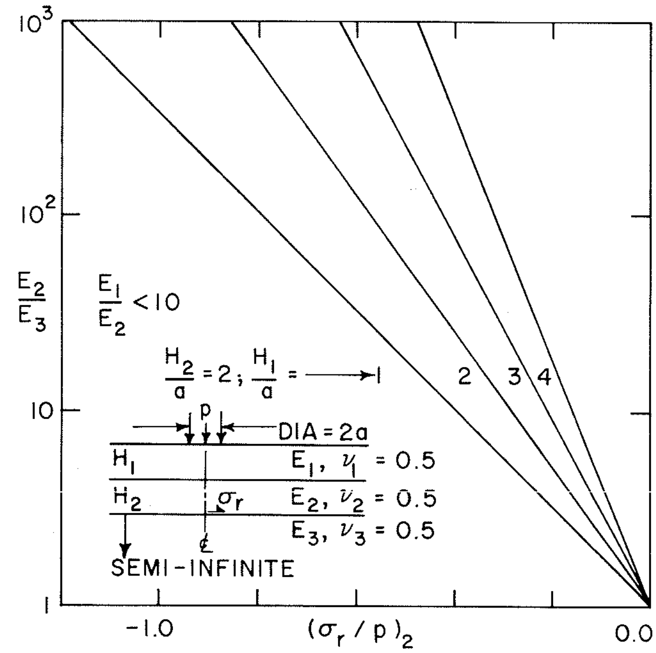


FIGURE 6 Ratio of maximum tensile stress to surface pressure at the base of the second layer of a three-layer semi-infinite elastic medium subject to a uniform circular surface load.

EARTH COMPACTION

Early earthwork practice permitted the construction of embankments and subgrades without compaction. Transportation support systems were not placed on completed subgrades for many months to allow natural consolidation. Unfortunately, detailed observations have shown that consolidation of most soils by nature alone is inadequate and results in many failures due to the lack of adequate compaction. Indeed, failures often occur on clay embankments where compaction has been undertaken (*10*). Such observations become clearer under heavier loads such as those associated with heavy-axle cars. Adequate compaction assures three main factors that are desirable for good embankment, subgrade, and track performance: (*a*) a decrease in the susceptibility of the soil to settlement, (*b*) a decrease in the permeability of the compacted subgrade soil, and (*c*) an increase in the soil's supporting power [e.g., California bearing ratio (CBR)].

Figure 7 shows how these three criteria are satisfied. Starting at the base of the figure and working upward are shown (*a*) a typical density curve, (*b*) a zero air voids or complete saturation curve, and (*c*) a penetration resistance curve.

Settlement is mainly caused by reduction in volume, which is caused by compression of the voids (unless failure is evident). The least value obtainable on the complete saturation line corresponds to the highest value of dry density obtainable for the constant compactive effort curve considered.

Because water must permeate the void space, obtaining a minimum void volume generally means obtaining a minimum permeability. Capillary water movements are also minimized—again indicating the importance of maximum density.

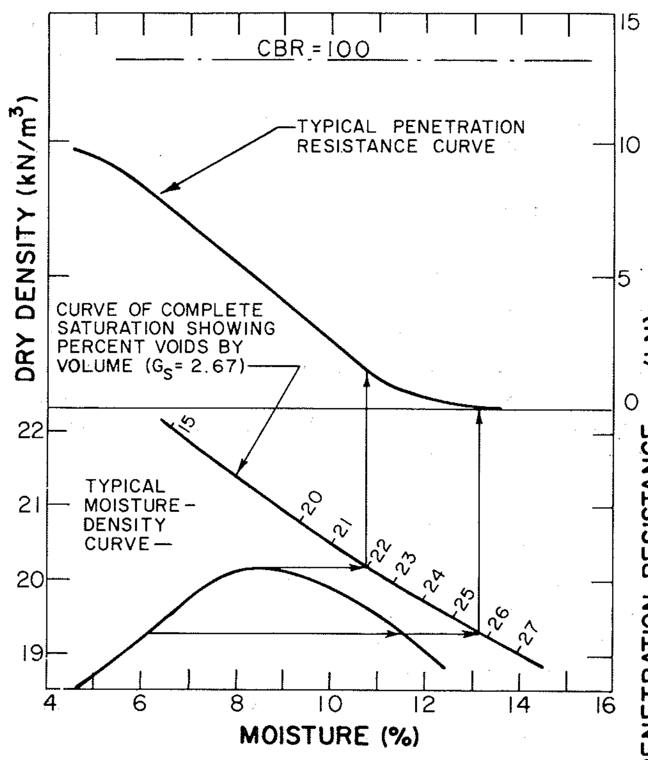


FIGURE 7 Typical soil compaction data showing density-moisture relationship and zero voids curve below typical penetration resistance-moisture relationship.

Bearing capacity related to the compaction curve is also shown in Figure 7. Clearly, when the soil is not saturated its bearing capacity can be large. On soaking and saturation, however, the soil's bearing capacity for a given density drops to that corresponding to the zero air voids or complete saturation curve. For a given density-moisture curve, maximum soaked or saturated penetration resistance occurs at maximum density.

CEMENT STABILIZATION

Cement stabilization involves breaking up (pulverizing) the soil to be treated, adding cement, mixing the cement with the soil, and then watering and compacting in the usual manner. It is generally about 30 percent cheaper to combine the cement and soil in place than to batch mix. Thus in-place mixing is the most common method of treatment. When the cement hydrates, the soil is stabilized and will be stronger and more resistant to penetration by water and other materials. Care must be taken to avoid soils that have more than 1 to 2 percent organic matter and those with sulfate contents greater than 5,000 ppm SO_4 (*11, 12*). Even 2,000 ppm SO_4 or less may be cause for concern. Where soils with high sulfate contents are used, seal coats of waterproofing should be applied. Seal coats should also be used on so-called swelling soils. Sulfate action causes disintegration and softening of the cement-stabilized soil when the moisture content exceeds that necessary for compaction. This may occur at any time, even after several years of satisfactory performance. In the opinion of the writer, seal coating and good drainage are the only reasonable defense where sulfate soils must be used. They are also considered necessary with so-called swelling soils.

The addition of small quantities (1 or 2 percent) of cement will modify the properties of soil; larger amounts (4 percent or more) cause major property alterations; and very high percentages cause concretelike materials. The effects of the two processes—cement modification and stabilization—differ principally by degree. Recent practice for subgrade stabilization work has tended away from the practice of producing concretelike materials (i.e., very high percentages of cement). More common is stabilization of the soil to maintain mechanical stability. (An exception is the stabilization of water-retaining structures such as open canals.)

The Portland Cement Association in its *Soil-Cement Laboratory Handbook* (*13*) outlines a method of obtaining the amount of cement required to stabilize a soil. The first estimate is given in Table 1. Laboratory moisture-density tests may then be performed using cement values in 2 percent increments of those given in Table 1. A 7-day soaked unconfined strength of about 1.75 MPa is generally acceptable for railway subgrades.

Ordinary portland cement is the most commonly used cement stabilization material. Additives are sometimes used; however, their use should be treated with caution. Incorrectly proportioned quantities may be detrimental to stabilization. The main exceptions are the use of small quantities (2 percent) of lime to aid pulverization in high-plasticity clayey soils (*14*) and pulverized fuel ash (fly ash) or natural materials that act as a pozzolan (ASTM C 618).

TABLE 1 INITIAL CEMENT ESTIMATE (*13*)

AASHO Soil Group	Percentage Cement by Weight
A-1-a	5
A-1-b	6
A-2	7
A-3	9
A-4	10
A-5	10
A-6	12
A-7	13

Cement-stabilized soil should be compacted as soon as possible after mixing; otherwise hydration begins (*14*) and the soil's strength builds up in clods, which results in an overall strength reduction due to the difficulty of compacting the soil. If correctly compacted, the soil cures to a stiff material with a deformation modulus in the range of 0.14 to 20.0 GPa (*14*). On the basis of Figure 6 it is apparent that cracking is highly likely. Indeed, many consider that the correct treatment of cement-stabilized layers is to allow traffic access as soon as possible after construction (*15*). Such a procedure recognizes that cracking is likely to occur and permits fully cracked interlocking to develop early.

Accepting the probability of cracking suggests a cement content sufficient to result in a 7-day soaked unconfined strength of about 1.75 MPa (*14*). To limit shrinkage cracking, a compaction moisture content 1 to 2 percent dry of optimum and never greater than optimum is generally specified (*14, 15*). (Note that this is different from untreated soil specifications in which 1 to 2 percent wet of optimum is used to enhance workability.)

Where moisture must be kept from the subgrade, the surface is sealed with an asphaltic or mastic seal (*16*). Such an asphaltic seal might consist of a mixture of (*a*) 65 to 80 percent by weight 120 to 150 penetration grade asphalt heated to from 175°C to 205°C, (*b*) 20 to 35 percent ground tire rubber of sieve size No. 16 to No. 25, and (*c*) 5 to 7.5 percent kerosene to reduce viscosity for spraying (*16*). After application, some 10-mm-sized chip screenings are added. Several layers may be applied over swelling subgrades. Good drainage is, of course, essential. This is true for all good subgrade performance.

A series of articles and design guides is available from the Portland Cement Association (Skokie, Illinois 60076).

LIME STABILIZATION

Stabilization of soils with hydrated lime is similar to cement stabilization. It is generally used on high-liquid-limit clays and is rarely used with granular soils unless they contain plastic fines. Lime or lime slurry may be added as a soil conditioner. Lime is thus a versatile stabilizer of clay subgrades (*14*).

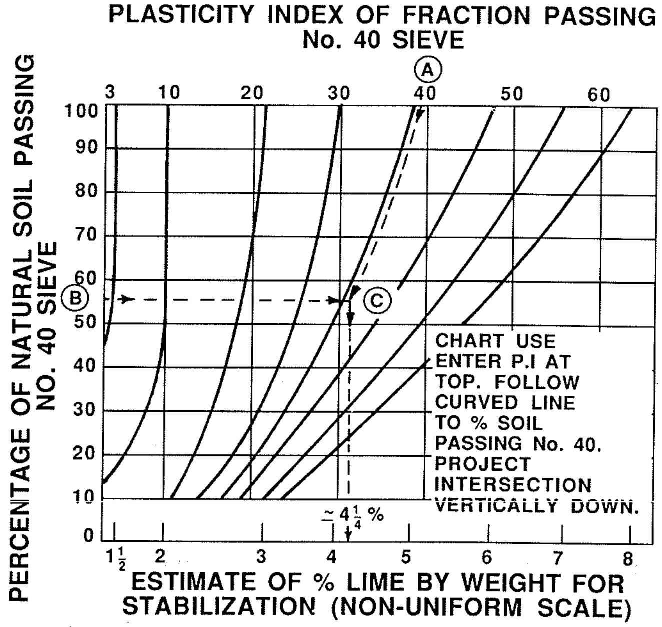


FIGURE 8 Guide for obtaining percentage of lime for stabilizing clay and silt soil fractions within natural soils (*18*).

Lime stabilization is achieved with calcium hydroxide (hydrated lime) or calcium oxide (quicklime). Because of environmental considerations, the former chemical is more commonly used. Both have a high percentage (about 90 percent) of calcium and magnesium oxide present. The stabilizing effect results from chemical action and the formation of cementitious compounds (calcium silicates). Calcium carbonate (agricultural lime) does not form silicates and is unacceptable as a stabilizing material (*14*).

Organic soils and sulfate soils need the same type of special attention that cement-stabilized soils require. Similarly, most additives except fly ash are of questionable value.

Unlike cement-stabilized soils, which need compaction as soon as possible after mixing, lime-stabilized soils require a 72 hr rot period after mixing and compaction (*14*). Lime-stabilized soils generally increase in strength with the addition of lime up to a given limit above which additional lime has little value (*14*). In frost penetration areas, a strength of 1.4 MPa is generally considered effective against frost action (*17*). For some soils several months of cure time will be required to obtain this strength (*17*).

Again it is important to perform preconstruction tests to determine the suitability of lime stabilization and obtain the cure times required. An approximate estimation of the lime requirement may be obtained from Figure 8 (*18*). An example of the use of this chart is given for a soil that has a plasticity index of 39 and a percentage passing the No. 40 sieve of 55. These data are entered on the chart as Positions A and B, respectively. Following the curved lines downward from A to the intersection of a horizontal line from B gives Point C. Point C is projected vertically downward to give the estimate of the required percentage of lime by weight.

An extensive series of articles and design guides is available from the National Lime Association (Arlington, Virginia 22201).

GROUT AND LIME SLURRY PRESSURE INJECTION

On chronically unstable clay subgrades under existing track it will be essential to undertake some form of subgrade or embankment strengthening before heavier axle-loaded cars are introduced. Lime slurry pressure injection (LSPI) roadbed stabilization is an accepted procedure (*19*) used throughout the United States by most of the major railroads to treat high-maintenance, chronic track problems associated with high-plasticity soils. Cement and cement grout injection are also used in deep ballast pockets (*10*). The slurry is injected into the ground under pressure forcing free-water pockets to be drained and forming a network of strong stabilization seams. The slurry is distributed in vertical and horizontal sheets throughout the soil mass as it flows through available voids, fissures, dessication cracks, failure planes, and coarse geologic formations. Certain physicochemical changes occur at the interface of the grout seams, where direct contact is made with the soil, as well as in the soil between the seams because of supernatant impregnation. The stabilized grout-impregnated seams form impervious moisture barriers that impede the movement of moisture and add considerable strength and reinforcement along the former zones of weakness and dislocations. In certain instances multiple injections are used to achieve increased stabilization by creating a more extensive network of seams. The larger fissures and voids are usually filled by the initial injections. The second injection allows the slurry to penetrate small cracks and thus achieve a denser distribution of slurry in the soil mass.

The purpose of grout and lime injection is to improve track stability by (*a*) reducing the water-holing capacity of the ballast pockets; (*b*) sealing, where possible, the ballast-subgrade interface (the writer doubts that this is possible on a long-term basis from grout injection only); (*c*) impeding the movement of moisture in the subgrade by forming relatively impervious seams throughout the treated mass; (*d*) increasing the strength of the treated mass through physicochemical reactions between the soil and the lime and fly ash; and (*e*) reducing the volume change potential of the subgrade clays. The techniques involved are best performed by a specialist contractor who has had extensive experience with injection processes. After treatment, undercutting and ballast cleaning and replacement are advisable along with the possible installation of a subballast or geotextile.

Some articles and design guides on lime slurry pressure injection are available from the National Lime Association (Arlington, Virginia 22201).

CAUSES OF UNSTABLE SUBGRADES—SEPARATION REQUIREMENTS

Irrespective of the amount of compaction a subgrade receives during construction, some degree of permanent deformation occurs because of traffic loading. This loading is greatest below the rail, which causes the formation of a depression in which water may collect. On good subgrades, this depression may be only millimeters deep, but this depth can be sufficient to cause water ponding and softening of impermeable subgrades. To prevent silt-sized fines from penetrating upward from such subgrades, nonplastic sand-sized materials grading continuously and gradually down to the 74-micron (No. 200) sieve should be included in the subballast, or a nonplastic sand-sized granular capping material should be provided on the fill or subgrade. This capping material should act as a filter to prevent fines from being vibrated or pumped upward. Similarly, subballast should be continuously and gradually graded to prevent it from vibrating upward into the ballast. A nonwoven geotextile may be used to meet this latter require ent. A geotextile, however, only acts as a partial filter to silts or clay. Typical gradings recommended by the writer for use by Canadian National Railway and Canadian Pacific Railway are given in Table 2 (*20*).

It should be clearly understood that the dynamic loading experienced within a railway track support fill is much greater than that generally experienced by any highway support system. As has been shown (*1, 2*), impact loading from wheel flats or out-of-round wheels can impose dynamic loads several times those due to static loading. Modified-clay subgrades, which form a brittle, hard subgrade surface, are generally subject to cracking and must be covered by a nonplastic granular filter material. As wheel loading is increased from 100-ton cars to 125-ton cars, these suggestions will clearly be even more relevant.

Even where subgrades or fills adjoining the subballast are well compacted, dry summer weather may be expected to cause drying of the surfaces in contact with the subballast. Wetting after such dry weather may then be expected to cause collapse of the soil structure of the subgrade surface, which accelerates the erosion of fines upward into any unprotected ballast or substandard subballast. Over time such erosion could be expected not only to foul any substandard subballast but also to foul the ballast. Once fouled, both materials may be expected to heave during freezing weather. The writer cannot overstress the importance of using suitably graded subballast that will remain unfouled by eroding fines from any underlying material. The subballast should also be suitably graded so as not to itself be vibrated upward and foul the ballast. Interface drainage is also of great importance. The subballast material must be nonplastic so as to deform (or collapse) easily by flowing and not cement. Cementing would permit vertical fractures.

TRACK SECTION

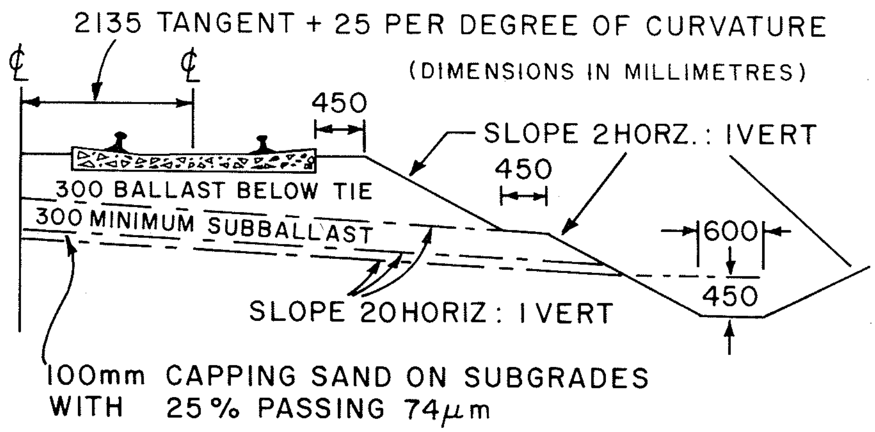
The exact construction of a given track section is clearly a designer's responsibility and should be based on site-specific data and costs. Figure 9 shows a summary cross section indicating the probable main requirements for major two-track installations for tracks carrying 125-ton cars. Figure 9 incorporates the following recommendations from the *Manual for Railway Engineering* (*8*): (*a*) 3.6 m center to center between track centerlines, (*b*) a 0.45-m berm at the upper level of the subballast to allow future track raising without ditch filling, (*c*) a ditch 450 mm below the discharge level of the prepared (compacted) subgrade, (*d*) a 300-mm minimum ballast depth, and (*e*) a 300-mm minimum subballast depth. In addition, Figure 9 shows recommendations, considered justified for quality track with low maintenance, that are more demanding than those specified in the AREA manual. These are (*a*) a 5 percent gradient to the prepared subgrade, (*b*) 450 mm of ballast shoulder as opposed to 150 mm, and (*c*) a 600-mm-wide ditch invert as opposed to a V-shaped base. Other factors shown, which are nonrigid recommendations of the AREA manual, include (*a*) a 100-mm sublayer indirectly specified by AREA as needed where pumping is likely to occur (i.e., a suitably graded subballast layer is needed on pumpable subgrades) and (*b*) a suitable method of partial frost cover protection in cold climates.

Some railroads use less ballast and subballast than recommended by the AREA manual (*8*, Article 1.2.5.4). As tampers are made more powerful to achieve greater productivity, their tamping tines become larger. Their movement back and forth moves ballast to a depth of 200 mm. Assuming a settlement between tamping of 50 mm, it is apparent that a 300-mm

TABLE 2 SUBBALLAST GRADING LIMITS (*20*)

Sieve Size	Capping Sand[a]	Filter Sand[b]	Open-Graded Subballast[c]	Broadly Graded Subballast
1 in.		100	100	100
1/2 in.			51-100	51-100
3/8 in.		80-100	30-80	48-80
No. 4	100	65-100	0-15	40-65
No. 8		55-85	0-3	
No. 16	70-100	45-70		25-45
No. 50	25-70	25-45		10-25
No. 100	14-40	14-30		5-14
No. 200	5-15	5-15		3-5

Note: Ballast shall not be placed directly on capping sand.
[a]Capping sand shall be covered by 280-g/m^2 nonwoven needlepunched geotextile.
[b]Filter sand should, preferably, be covered by open-graded subballast or 280-g/m^2 nonwoven needlepunched geotextile on heavy-tonnage lines.
[c]Open-graded subballast to be used only on filter sand or on nonwoven needlepunched geotextile.



- CAPPING SAND TO MEET ASTM D1241 AND BE CONTINUOUSLY GRADED WITHIN GRADING LIMITS D, E OR F OF D1241.
- SUBBALLAST IF USED WITHOUT CAPPING SAND SHALL MEET A.R.E.A. Ch. 1, ART. 2.10. - WHERE CAPPING SAND COVERED BY A GEOTEXTILE IS USED, SUBBALLAST GRADING SHOULD BE VOID OF SIZES LESS THAN 3mm.
- IN HIGH FREEZING INDEX LOCATIONS REQUIRED GRANULAR COVER MAY BE REDUCED 15 THICKNESSES FOR EACH THICKNESS OF STYROFOAM HI-60 OR SIMILAR. STYROFOAM TO EXTEND 1300mm BEYOND TIE ENDS AND TO BE PLACED ON GEOTEXTILE THAT IS ON 100mm SUB-LAYER. STYROFOAM MAY NOT BE USED TO REDUCE GRANULAR COVER REQUIRED DUE TO WEAK SUBGRADE.
- MINIMUM FROST PROTECTION GRANULAR COVER TO BE 50% OF FROST DEPTH GIVEN BY AVERAGE YEARLY FREEZING INDEX.
- BALLAST - HARD MINERAL - TOUGH - LOW AGGREGATE INDEX. GRADING A.R.E.A. No. 4 OR 24

FIGURE 9 Typical track cross section for new double-track construction (*20*).

ballast depth is minimal for high-quality track subject to high-production tampers. Similarly, as dynamic loading increases with vehicle speed, minimum subballast depths, on new construction, of 300 mm are recommended.

GEOTEXTILES FOR RAILWAY TRACK APPLICATION

Extensive research and findings have previously been reported on the use of geotextiles in railway track applications (*20-22*). Details of recommendations for use of geotextiles and a user specification can be found elsewhere (*20*). By far the most important aspect of geotextile use is good drainage because subgrade pumping requires a water source.

BALLAST SPECIFICATION

The detailed requirements of ballast for 125-ton cars are likely to change little from those for 100-ton cars. Heavier loading may, however, tempt the track engineer to consider the use of concrete crossties, which require careful ballast selection. Because concrete is made from silica sands, the majority of minerals of which are harder than Mohs' hardness scale of 5, the predominant minerals in the aggregate source used for the ballast with concrete ties should have Mohs' hardness values of 5 or greater. Otherwise, the silica sand minerals making up the surface of the concrete tie are likely to powder the ballast by abrasion and scratching. Further details on ballast selection are given elsewhere (*23*).

TRACK DRAINAGE

As stated earlier, good track drainage is essential to subgrade longevity, particularly in wet climates. Both subgrade strength and the minimizing of particle migration are facilitated by good drainage practices. Such practices include (*a*) adequate side-ditch drainage to deal with surface water, (*b*) lowering the groundwater to increase subgrade strength, and (*c*) internal drainage or cross-fall sloping of subgrade and subballast surfaces to prevent water seeping into the subgrade load-bearing area. Internal track drainage is by far the most difficult improvement to ensure on rehabilitation work; however, on new construction, both the subgrade and subballast layers should be constructed with a 5 percent slope as illustrated in the typical cross section shown in Figure 9 for a two-track line.

In any corrective work involving the use of subballast or geotextiles, proper and adequate drainage must be included in the planned maintenance. The elevation of the discharge level must be lower than that of the track-bearing area of the undercut surface. Although granular material for track support may be required to reduce subgrade stresses to an acceptable level, geotextiles within the track structure should be selected only on the basis of their handling strength requirements and their ability to separate, filter, and otherwise facilitate drainage. Of particular importance is the geotextile's ability to facilitate drainage by transmitting water within its plane. Incorrectly installed geotextiles will facilitate drainage into the load-bearing area of the track. Their discharge elevations must be lower than the undercut elevation directly below the track.

In rehabilitation work using undercutters, attention to drainage is unfortunately sometimes neglected (*22*). Special attention should be given to the undercutting of long lengths of track where a "canal effect" is often produced. If, after or before undercutting, the shoulder ballast is not removed and cleaned, drainage cannot occur from the load-bearing area to the side ditches. Where possible, the shoulder undercut should be deeper than the track undercut. On flat and marshy land, French drains may be required. Similarly, short lengths of undercut track such as grade crossings that are not subsequently, or during undercutting, provided with drainage will result in a "bathtub effect." Grade crossings also suffer from lack of drainage along the width of the highway. They should be provided with French drains through the crossing that discharge into side ditches beyond the crossing's limits. Water that is trapped within the load-bearing areas of the track can be expected to provoke or stimulate pumping along with the possibility of frost heave during cold weather.

Where French drains include pipes, the pipes should be laid at gradients that are self-cleaning. Table 3 gives the values of minimum gradients for various pipe sizes so that they self-clean when flowing half full and transmit water at a velocity of 600 mm/sec when full.

TABLE 3 MINIMUM GRADIENTS FOR SEWERS TO BE SELF-CLEANING

Diameter of Pipe (mm)	Gradient (in.)
150	240
175	295
225	415
300	610
375	820
450	1,050
525	1,300
600	1,500

CONCLUSIONS

The main points concerning the performance of railway track subgrades have been outlined and the following conclusions reached:

1. On the basis of theoretical suggestions previously made by the writer (*1*), it is concluded that the ballast raises shown in Figure 2 are the maximum necessary to maintain subgrade stresses below 36-tonne static axles at values less than those below 30-tonne static axles.

2. Conclusion 1 also applies to dynamic considerations provided the maintenance limits associated with wheel or track irregularities are maintained.

3. Where factors of safety are presently safer than necessary for 30-tonne axles, the theory will allow an assessment of the necessity of using a ballast raise. Such an assessment must be done on a case-by-case basis.

4. On new construction, adequate subgrade compaction assures three main factors that are desirable in good subgrade and track performance: (*a*) a decrease in the susceptibility of the soil to settlement, (*b*) a decrease in the permeability of the compacted subgrade soil, and (*c*) an increase in the soil's supporting power (e.g., CBR).

5. On new construction where granular cover exceeds 305 mm ballast plus 150 mm subballast, a makeup depth of stabilized-soil material may be used. This depth should be considered equivalent to a similar depth of unbound material because of the extensive cracking that Figure 6 predicts.

6. Great care must be taken when using soil stabilization if the treated soil is high in sulfates (*11, 12*). Both good drainage practice and the use of a seal coat are recommended.

7. A graded granular subballast that will act as a filter to the subgrade is an essential requirement above treated-soil subgrades and other fine-grained subgrades. Alternative subballast possibilities are given in Table 2.

8. Geotextiles and lime slurry pressure injection have been shown to be viable subgrade improvement techniques on existing track.

9. Good drainage practice is essential for subgrade longevity. Good drainage practice also minimizes the probability of fines separating and pumping from the subballast.

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