Granular Depth Requirement for Railroad Track

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ABSTRACT

In late 1962 severe deterioration of the CN Rail Mountain Region Sangudo Subdivision roadbed occurred following introduction of six-axle locomotives and 100-ton sulphur car traffic. Studies concluded that subgrade soils were being overstrained. In 1977 some 25 theoretical roadbed design theories were identified in a report by the Federal Railroad Administration, but none of them had been simplified or validated to the stage where they had been adopted by practicing railroad engineers. In 1963 British Rail Research embarked on an investigation to evolve a comprehensive design method for railroad track foundations, and in 1972 they published granular depth design charts based on soil stress threshold levels and vehicle axle loadings. The design charts did not appear to correspond with CN Rail Research Centre experience, and in 1979, the Centre embarked on a 4 1/2 year investigation of roadbed behavior. In this study, wheel loadings, tie plate loadings, tie deflections, roadbed deflections at depth, rail settlements, and subgrade surface settlements were measured. In addition, McGill University Geotechnical Research Centre was retained to investigate subgrade soil dynamic triaxial test and creep test properties. Although field measurement and laboratory test work has been terminated, not all of the information has been correlated. Some of the findings from the field measurement work are presented in this paper.

Faced with significant increases in projected traffic, CN Rail in the late 1970s embarked on a new track construction double tracking program in Western Canada. Traffic densities were not only increasing, but the percentages of heavy axle loadings from 100-ton cars were also increasing. With rising costs of track construction and track maintenance, it was imperative that proper granular depths be selected for the new track. Remembering the Sangudo Subdivision experience, requirements for upgrading existing lines before introduction of new traffic were also a prime consideration.

At the outset of the roadbed investigation research program, some difficult questions had to be answered. What track measurements should be taken? How should instrumentation be deployed in order to collect information in a short time frame? How was information to be analyzed and correlated? British Rail Research had measured roadbed stresses (with difficulty), and had concluded that stress levels could be predicted with acceptable accuracy through use of the Boussinesq equations and knowledge of tie loadings. It was believed that there was no requirement to repeat the British Rail stress measurement and theoretical validation.

For the initial field measurement work, it was decided to measure tie plate loads, tie deflections, and subgrade surface deflections at 12 Edmonton area sites with variable depths of granular and variable traffic conditions. Subgrade materials were under the general category of Lake Edmonton clays. The instrumentation setup was as shown in Figure 1. Standard 14-in. tie plates, each fitted with four strain-gauged button load cells, were used to measure vertical tie plate loads. To determine the depth of granular at each site, holes were dug outboard of tie ends midway between the two selected ties. A 2-in. diameter hole was then augered into the subgrade soil, and a 6-ft 1.50-in. diameter plastic pipe was inserted. A 9-ft 1-in. diameter steel benchmark rod was then driven into the subgrade. To measure subgrade surface deflections, an encased rod with cone was driven through the ballast and subballast until the cone was embedded in the top surface layer of the subgrade. The rod and cone were then driven an extra 0.50 in. to free them from the casing. Foam rubber compressed between rod and casing minimized lateral vibrations but did not affect vertical movement of the rod. Spring-loaded displacement transducers attached to the benchmark rod were used to measure tie and subgrade surface deflections.

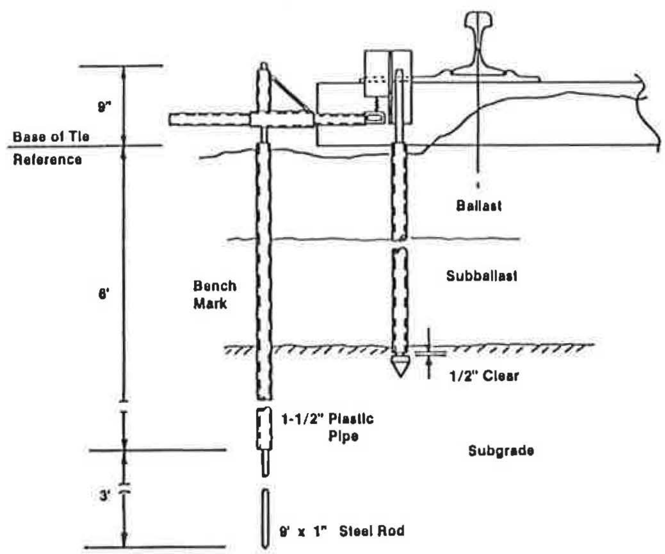

FIGURE 1 Instrumentation setup.

CN Rail experimented with using accelerometers as inertial references to eliminate the benchmark rod, but without success. It is doubtful if the 9-ft benchmark rod provided an absolute reference, but the deflections should have been small relative to those at subgrade surface. Data were recorded on an 8-channel chart, with individual loads and deflections displayed as well as simultaneous average tie loads and tie deflections.

As shown in Figure 2, average tie and subgrade deflections were plotted against tie plate average loads to determine tie and subgrade compliance values. Plots of this type were found necessary to eliminate initial softness and nonlinearity in tie support conditions. The excellent relationship between tie and subgrade deflection is shown in Figure 3, where 56 percent of the roadbed deflection occurred within the subgrade at this site.

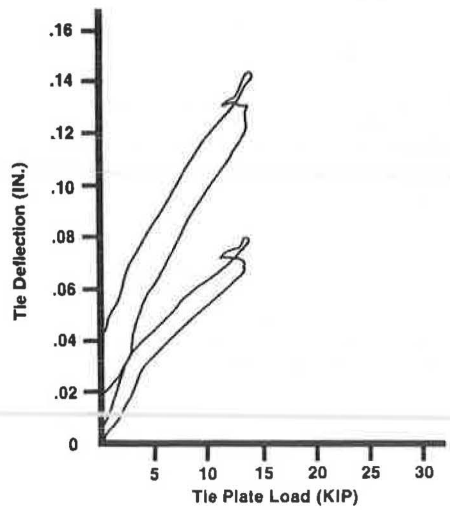

FIGURE 2 Tie and subgrade deflections.

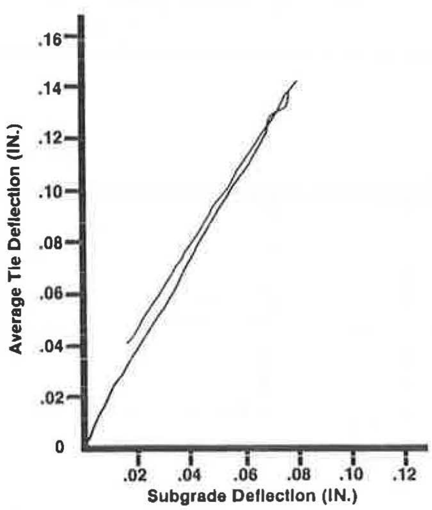

FIGURE 3 Tie versus subgrade deflections.

A substantial amount of chart reading and graph plotting was required to develop this type of information for the 12 measurement sites. The ratio of subgrade to tie deflection for the 12 sites is plotted against depth of granular as measured from base of tie in Figure 4. The data fit is surprisingly good considering the relative crudeness of the measurement system. One of the points off the curve resulted from frozen roadbed (measurements were taken in early May 1979), and the other two points represent data scatter, the bugaboo of track measurement researchers. It should be noted that the curve simply shows a ratio of measured track deflections and is independent of track loading. At 20-in.

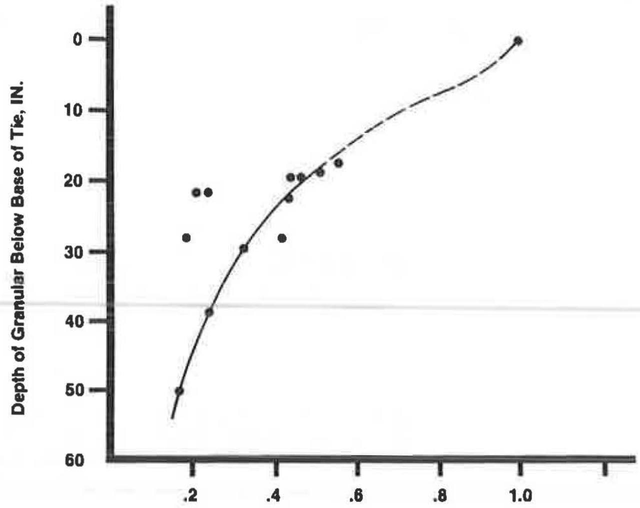

FIGURE 4 Proportion of total deflection within subgrade (C_S/C_T).

granular depth, 50 percent of the track deflection came from the subgrade and 50 percent came from the granular layer, whereas at a depth of 50 in., less than 20 percent of the total deflection came from the subgrade. The relatively good data fit was most encouraging, because it meant that the roadbed behaved in a logical manner, and that a simple means had been found to document that behavior. Once organized, it was possible to measure two sites per day.

The deflections of both tie and subgrade, normalized per kip of tie plate loading, have been plotted in Figure 5. There is reasonably good fit for both curves, but it is apparent that there is less scatter in the subgrade data points. Ties tend to flop around, but subgrade is more sedate and well-behaved. Through the previously mentioned procedure of plotting tie load-deflection curves, an attempt was made to eliminate tie slack and initial spongy deflection from the results, but it is clear that it was not entirely successful. There is one somewhat surprising result in this graph in that the tie and subgrade curves are roughly parallel. The difference between the two curves represents the amount of deflection that occurred within the granular layer, and this deflection appeared to be relatively con-

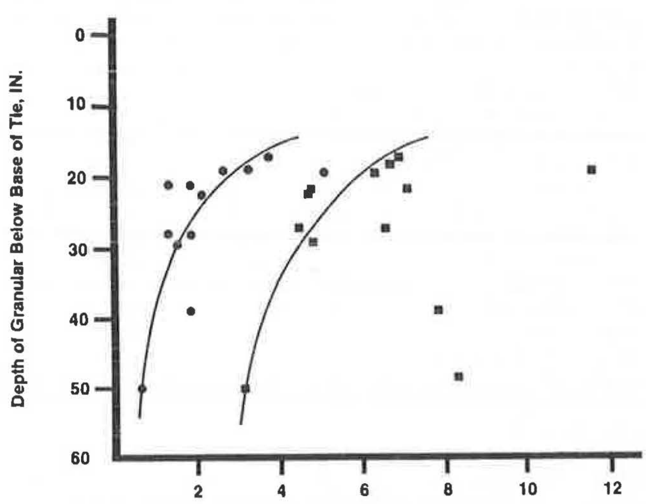

FIGURE 5 Normalized subgrade and tie deflections.

stant for granular depths ranging from 17 to 50 in. It is believed that, with shallower granular depths, a significant portion of the granular deflection comes from shear deformation, whereas at greater depths, the granular layer undergoes compressive deformation with very little shear.

The absolute peak subgrade deflections have been plotted against depth of granular as shown in Figure 6. The curve has been drawn through the lower data points because they represent the higher deflections, and it was desired to adopt the conservative data approach. At 19-in. granular depth, the subgrade deflected eight times more than it did at 15-in. depth. There are three small kick-off curves shown below the main curve that trace the deflections that occurred 6 in. below the top of subgrade. The coned subgrade rods appeared to be giving satisfactory results, and it was believed that if a series of rods could be driven to different depths in the subgrade, then the elastic deflection curve could be plotted and the subgrade soil strains could be determined. These three trial measurement sites indicated that the apparently crude rod system could be used to measure subgrade soil strains.

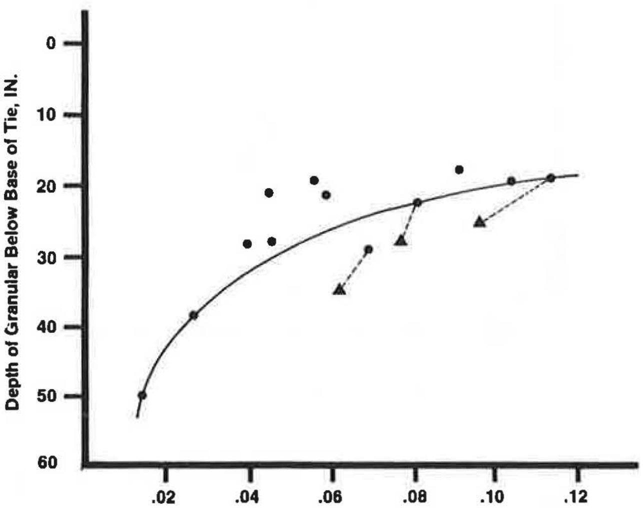

FIGURE 6 Peak subgrade deflections.

Reflecting on the main curve, it will be realized that it could be used as a granular depth design chart provided a level of subgrade deflection could be specified that should not be exceeded. For example, if 0.04 in. was specified as maximum permissible subgrade deflection, then roughly 32 in. of granular depth would be required. Unfortunately, no such subgrade deflection limits have been defined. There are shortcomings in this simplistic approach in any event, because traffic density has not been taken into account. The curve is, however, attractive from another viewpoint. Wheel and tie loadings need not be measured to generate this graph, and the problem of how to deal with load spectra has been largely eliminated. Hundreds of chart readings and plot load-deflection curves need not be taken in order to normalize the subgrade deflections with respect to load. It is necessary only to scan the charts, read the peak deflections, and assume that they represent the worst loading conditions that need to be considered. Data analysis time with this approach was reduced by a factor of 20.

A number of conclusions were drawn as a result of the 1979 Edmonton area measurements.

- The tests demonstrated the feasibility of using simple instrumentation to rapidly obtain useful track and subgrade elastic deflection measurements.
- There was a fairly well-defined relationship between tie and subgrade elastic deflection and depth of granular in track.
- This relationship was established without specific knowledge of granular or subgrade properties.
- The tie and subgrade deflections could be defined as a function of tie loading or as an envelope encompassing maximum deflections from the upper end of the track loading spectrum (without having to measure the actual track loading).
- The curves relating tie and subgrade elastic deflections to depth of granular could be used as design charts if limiting elastic deflection criteria could be specified for the traffic on a territory.
- There was far less variation in subgrade deflection than there was in tie loading or tie deflection, indicating the desirability of working through deformation measurement at depth as opposed to load or stress measurement at the surface.
- Subgrade and tie deflections were directly proportional except at low loading levels where slack and initial sponginess came into play.
- For comparative tie loading levels, deformations within the granular layer were relatively constant for depths ranging from 17 to 50 in.
- In order to define granular depth design criteria, relationships among roadbed elastic deflections and strains, roadbed settlement rates, track loading spectra, and traffic density would have to be established. These would have to be correlated with acceptable track maintenance levels.

Encouraged by the 1979 results, it was recommended that work be continued in 1980. Three additional sets of elastic deflection measurements were taken in the Edmonton area, and subgrade settlement plates were installed at five Edmonton area sites. To combat the logistics of taking measurements 2,000 miles from home base, two test sites were established in the Montreal area. A series of elastic deflection measurements were taken at one site, and rail and subgrade settlement rates were measured at both sites.

The subgrade elastic deflection measurements taken at the three Edmonton area sites in June 1980 correlated well with the May 1979 measurements, indicating again that the subgrade was a reasonably well-behaved component of the track structure. Tie deflections and loads showed more erratic behavior, as they had in 1979, indicating that tie slack and ballast compaction were variables that affected results.

At these 1980 Edmonton sites, three cones were driven into the subgrade: one at subgrade surface, one at 5 in. below subgrade surface, and one at roughly 10 in. below subgrade surface. Plots of elastic deflection with subgrade depth were drawn, and subgrade strains were estimated from the slopes of the curves. The curves were somewhat erratic, and apparent soil strains at subgrade surface ranged from 0.06 to 0.16 percent.

At the Montreal Joliette Subdivision test site, four cones were driven to depths of 12.50, 22, 29.50, and 40 in. The track had 10 in. of ballast and 10 in. of subballast. It should be noted that one of the cones was within the granular layer. Tie plate loads were measured, and, in addition, wheel loads were measured with rail shear strain gauge circuits. By this stage of the study, it had been realized that wheel loads were a better indicator of traffic conditions than were the more variable tie plate loads.

Sample deflections from the four cones have been plotted against depth from tie base in Figure 7. The individual plots are for different wheel loads. The deflection curves were very smooth, indicating that the simple cones can be used to define the railroad track elastic deflection curve.

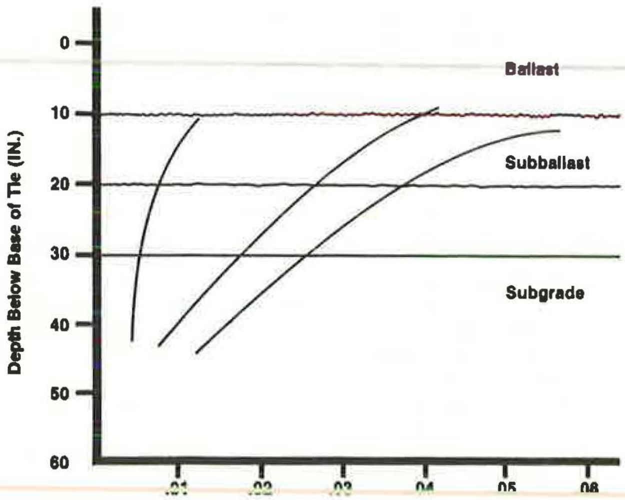

FIGURE 7 Subgrade deflections with depth.

Many of the roadbed theories available today have been presented as two- and three-layer theories. Substantive complications have arisen in trying to define and categorize the properties of the individual layers. As a result, these theories have never been validated and have never been used by railroad engineers. In Figure 7, the deflection curves run smoothly from the subgrade through the interface and into the subballast layer. Although these few measurements cannot be presented as absolutely correct, they do illustrate a significant point. Limited research dollars should be spent taking field measurements, where the true story lies buried in the existing roadbeds.

At the Joliette site, measurements were taken in August 1980, and the cones were left in place over the winter. From March 26, 1981, when the roadbed was frozen solid, to November 26, a series of 10 sets of elastic deflection measurements was taken with the same undisturbed setup. Soil strains were determined from the slopes of the elastic deflection curves, and these have been plotted against wheel load in Figure 8. Best-linear-fits were drawn through the scatter of data points for the 10 sets of measurements. The roadbed behaved as a solidly frozen block on March 26, was partially thawed on April 1 and April 23, and was completely thawed and soggy in May. In October and November, it had dried and stabilized. It will be noted that wheel loads have now been used in place of tie plate loads, and that soil strains at subgrade surface were on the order of 0.20 percent for 40 kip dynamic wheel loads. A tremendous amount of chart reading and data analysis work went into the preparation of this graph.

Unlike highway departments, railroads do not impose load restrictions during spring thaw. Of necessity they sometimes impose temporary slow orders at certain locations. The traffic must go through. Realizing that only the higher track deflections were significant, the envelope of peak strains has been plotted in Figure 9. This graph, requiring only

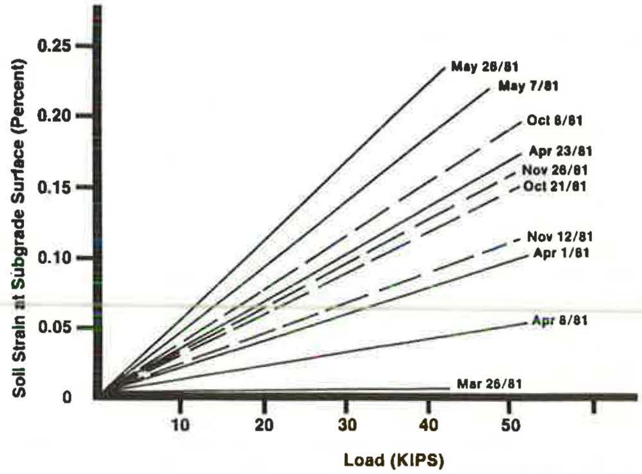

FIGURE 8 Soil strains.

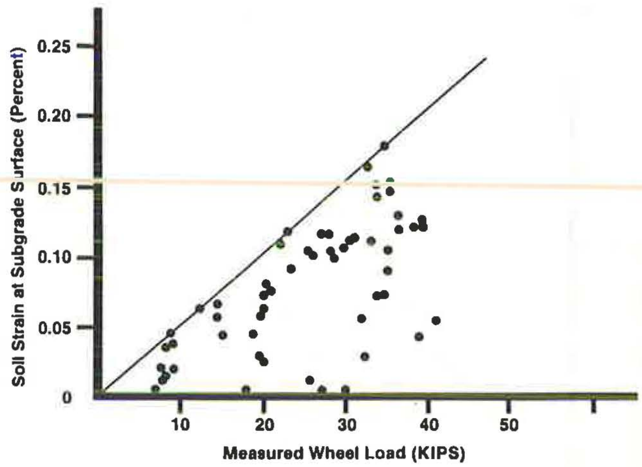

FIGURE 9 Soil peak strains.

a fraction of the work of Figure 8, shows the same peak strain relationship. This is termed simplification of data analysis, an important consideration in any longer term research project.

Having defined to some degree the roadbed elastic deflection behavior, the next problem was to relate this information to track maintenance requirement. Roadbed elastic deflection by itself is not necessarily harmful. Indeed, those railroads that have opted for rigid slab track construction have had to take great pains to reprovide elastic deflection from special pads. The requirement for track surfacing maintenance arises from uneven track settlement.

Track settlements were measured at five Edmonton area sites and two Joliette Subdivision sites. Six-inch square steel plates welded to 0.50-in. diameter rods were dug in to rest on top of the subgrade at a point midway between ties and just clear of the field side of the rail. At Joliette, elevations of rods were read with precise rod and level. For the Edmonton sites, pipes were welded to the settlement plates, and concentric benchmark rods were driven to depths of 9 ft. Settlements were recorded by means of special jig and dial gauge, measuring displacement between pipe and benchmark. At the Joliette sites, rail settlements were also measured with precise level.

A sample graph of rail settlement at one of the Joliette sites is shown in Figure 10. Frost heave of 4 to 5 cm or nearly 2 in. occurred each winter.

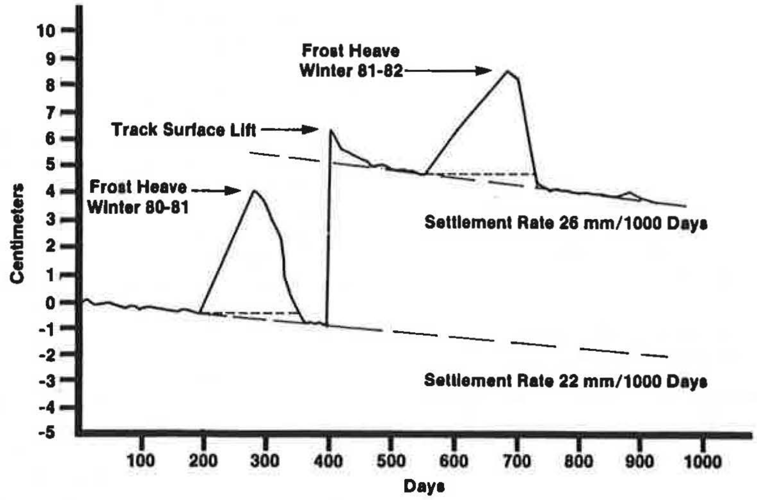

FIGURE 10 Sample rain settlement.

During spring 1981, a track surface lift of roughly 7 cm or nearly 3 in. was carried out. There are several points of interest in this graph. The rail settlement rate increased following the track lift, even after the initial rapid settlement stage. This graph is an example of why the British Rail development of the stone blowing technique, more commonly called troweling in North America, would provide significant benefits in track maintenance. The graph also shows that spring thaw settlements apparently continued at the same rates as those of the previous fall. Perhaps zero settlement occurred during the winter, and the extra little drop in spring brought the settlement rates into line. It is clear from this graph that the rail was settling.

During the course of the Joliette measurements, the track had also been skin-lifted and hand-tamped at the second site. As shown in Figure 11, the average rail settlement rate was 9 mm per year for both sites. Lifts of 6 mm or 0.25 in. were lost almost immediately, and even the 70 to 75 mm machine lift would be dissipated in 8 years. As the rates of subgrade settlement were far lower than the rates of rail settlement, it is speculated that there must be lateral migration within the granular layers.

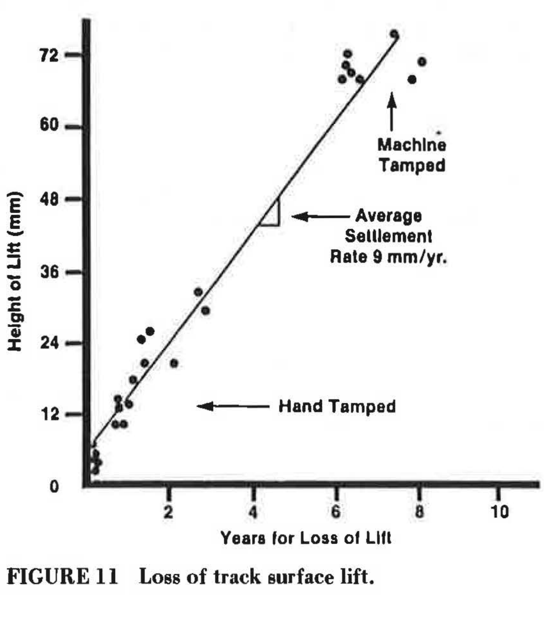

FIGURE 11 Loss of track surface lift.

The subgrade settlement rates in mm per month have been plotted against depth of granular as shown in Figure 12. The Edmonton area settlement points fell in a reasonably smooth curve, but settlement rates for the Montreal sites were lower. There are two explanations: the Edmonton subgrade consisted of 53 to 67 percent clay, 25 to 44 percent silt, and 3 to 8 percent sand, whereas the Montreal subgrade consisted of 15 percent clay, 50 percent silt, and 35 percent sand. In addition, traffic densities were heavier around Edmonton, and there were far greater concentrations of 100-ton cars. As track surface maintenance is conducted on a time schedule, the monthly or yearly rates of settlement could be useful for maintenance planning.

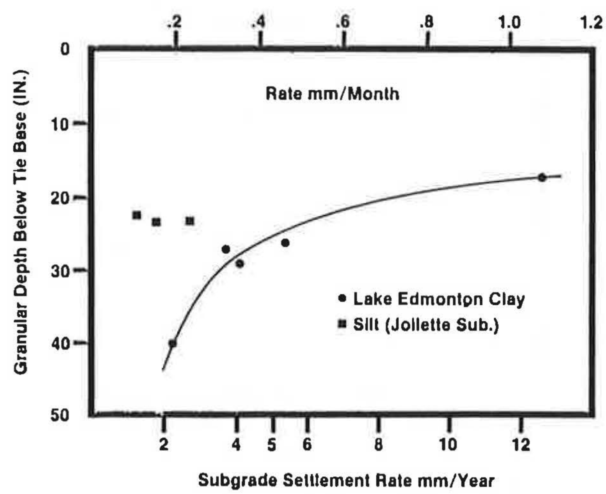

FIGURE 12 Subgrade settlement with time.

Subgrade settlement rates per million gross tons (MGT) of traffic have been plotted against depth of granular as shown in Figure 13. The curve fit is quite smooth for both the Edmonton and Montreal subgrade soil types. At 17-in. granular depth, the subgrade settlement rate was roughly 10 times greater than it was at 30-in. granular depth. If the traffic density at the 17-in. granular site was suddenly increased to the same level as at the 30-in. granular site, the track would literally sink out of sight and the Sangudo Subdivision experience would be re-

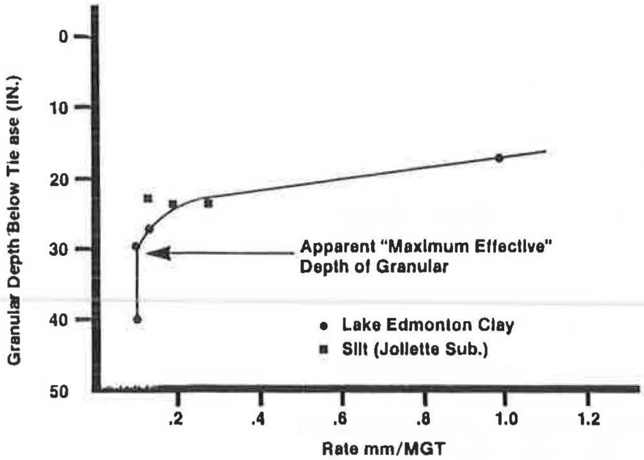

FIGURE 13 Subgrade settlement with traffic.

peated. Note also from this graph that no apparent benefit was derived in increasing the granular depth from 30 in. to 40 in. Although this graph has accounted for traffic density, it still has not taken account of track loading spectra, and there were significant differences in concentrations of 100-ton cars at the various sites.

Based on the amount of information available, but without any detailed assessment of the amount of track surface maintenance required at the various sites, it was somewhat arbitrarily decided that a subgrade settlement rate of 5 mm per year would provide for an acceptable track maintenance regime. A preliminary guideline for selection of granular depth requirement is shown in Figure 14. This applies basically to Lake Edmonton clays.

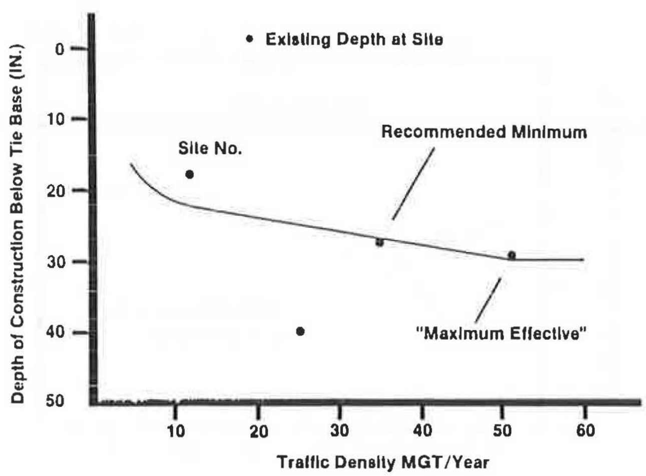

FIGURE 14 Preliminary granular depth design chart.

At the low traffic densities that are common on branch lines, granular depths of 17 to 20 in. would provide acceptable maintenance levels. At Site No. 17 with 12 MGT of traffic, 5 in. additional granular would be required to bring track settlement rates into line. At Sites No. 11 and No. 15, the granular depths appeared to be satisfactory for the current traffic densities of 35 and 50 MGT. At Site No. 14 with 40-in. granular depth and traffic at 25 MGT, there is far more granular depth than is required. The graph shows that there is little to be gained by increasing granular depths beyond 30 in.

Field measurement work was terminated in 1982, and McGill University laboratory soils work was terminated in late 1983. These terminations were the result of staff reductions and a heavy influx of more urgent shorter term projects. Railroad researchers are on the firing line, and they are far too few in numbers to enjoy the luxury of sitting in ivory towers.

It is not possible to state that this project has been successfully concluded, because there is still much cross-correlation of data that should be carried out. The final reports on field measurement and laboratory work at McGill University are still to be issued, and this paper is the closest that can be considered a project final report.

In retrospect, we undertook more than we could afford with our available resources, and we ran up blind alleys in some of the analysis work. However, the measurement and data analysis techniques required to complete the job have been developed, and those parameters that should and should not be recorded have been identified. Perhaps other railroad research agencies will continue this research.

What would have been preferable was a granular depth selection chart related to traffic density, track loading spectra, and a range of subgrade soil types. This chart would be directly applicable for new track construction and for existing tracks faced with significant increases in traffic. One of the problems with tracks constructed many years ago and having had many surface lifts in their lifetime is that nobody really knows how much granular depth is present. Although it could be determined through countless diggings, it would be far more practical if elastic deflections could be measured with a moving track modulus measurement car. Not only would soft spots be immediately identified, but the magnitudes of deflections would indicate how much ballast surface lift would cure the problem. The track geometry car surface roughness measurements in this study correlated quite well with subgrade settlement measurements, indicating a close link between depth of granular and track maintenance requirement.

It was too optimistic to believe that a 4 1/2 year study with limited resources would provide a usable granular depth selection chart. After all, after more than 100 years of railroading there is still no universally accepted roadbed design theory.

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