Model Studies of Track Support Systems

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Geometric, behavioral, and loading complexities create difficulties in analytical approaches to the prediction of track performance characteristics. The use of model testing as an alternative to more-expensive full-scale testing in providing direct results, as well as data for analytical correlation, is discussed in this paper. Equations of similitude are presented, and the choice of model scales and materials is considered. Model track systems at a linear scale-reduction factor of 6 were constructed and tested. The test variables were tie shape and spacing. Vertical and longitudinal repeated loads were applied in phase, and deformations were measured at various points in the structure. The conventional tie shape was found to be marginally superior to others tested, except for resistance to longitudinal loads. Minimizing tie spacing (or maximizing contact area) was found to be important for resisting continued settlements. The main purpose of the tests, however, was to demonstrate that model studies are capable of producing reliable results. Successful correlation with full-scale test results was achieved from the simplified model, and it is suggested that more-sophisticated real models could produce direct design information at significant savings in research resources.

Track-system maintenance is a cause of major expenditure in rail transport operations. Maintenance requirements are increased by the continued permanent deformation of the subgrade and track structure under repeated train loads. The track support system, however, must exhibit some flexibility to dampen the loading harmonics; an elastic support system would be ideal. Because soils (subgrade, embankment, and ballast) are not ideal elastic materials, the problem appears to be one of defining the conditions of placement and loading over which the system deformations will be mainly recoverable. Stiffening of the elastic system components (rail and ties) has been suggested [see, for example, Timoshenko and Langer (1) and Meacham (2)], but the steady increases in axle loads and train speeds make this alternative less and less attractive from both economic and track-stability considerations. The complex nature of the behavior of soil materials excludes analytical evaluation of the second alternative, namely, engineering a more-elastic response in the earth support system. This is particularly true in the rail track system due to the interactions of the various system components and the repeated loadings. The obvious approaches to an engineering solution are

1. Basic research to define the constitutive equations for the soil materials under appropriate test conditions, combined with the development of analytical techniques for predicting system performance, and
2. Model studies.

The first approach has gained research support in recent years, and considerable work is now in progress [see, for example, Raymond and others (3)]. The second approach does not appear to have been used to the same extent, although it would be desirable to develop both approaches in parallel for two reasons:

1. Although testing to provide soil parameters for analytical models appears to be a more fundamental approach, it must be acknowledged that soil mechanics tests are essentially model tests in that they are carried out on assemblages of discrete particles under various boundary conditions. Such tests may not provide self-consistent constitutive relationships, and empirical correlations may be necessary. Thus, although analytical predictions can be correlated with present prototype behavior, the predictions of behavior of new systems (alternative prototypes) are still empirical.
2. Model studies can be carried out on any alternative system (as well as the present prototype) and will provide an early preliminary evaluation of its potential for success. Even the results of imperfect models can be valuable in evaluating the relative importance of various parameters. Track system has a large number of independent variables, a factor that makes the use of model studies cost-effective.

The two approaches can, obviously, be complementary. Certain problems, such as the pumping or intermixing of ballast, subballast, and subgrade materials or the breakdown of ballast under repeated loading, can be evaluated by an imperfect full-scale model test in a large cylindrical oedometer. Such test data have been reported by Gaskin and Raymond (2). Problems that involve system interaction, however, require that the track system be represented. Full-scale testing is both expensive and time consuming. This paper discusses the modeling of track support systems, presents some model test data at the smallest recommended scaling, and makes some recommendations for future model studies.

DIMENSIONAL SIMILITUDE AND MODEL SCALES

The linear scale used for model testing of a conventional track support system will be limited by the prototype ballast-size distribution because the model ballast must exhibit similar characteristics. Figure 1 compares the Canadian National Railway specification A ballast and the model ballast, as well as the grain-size distributions for other layers, used in this study. The linear scale factor is $\lambda_L = 6$, and it is recommended this be considered a minimum model size (i.e., model $\geq \frac{1}{6}$ prototype scale) to produce similarity of the tie-ballast and ballast-subgrade interaction. Figures 1 and 2 show the similarity of test characteristics between the model and the prototype ballasts.

By considering the rail-tie system as a continuous beam on an elastic foundation and using Winkler's hypothesis (subgrade reaction is proportional to deflection at a point), the deflection and reaction are given, under static load, by Hetényi (5) as

$$y = (p\beta/2K)\, e^{-\beta X}\, (\cos\beta X + \sin\beta X) \qquad (1)$$

and

$$\sigma_{max} = (p\beta/2K)\,(S\,K/A) = p\beta S/2A \qquad (2)$$

where

y = rail deflection at a point located distance X

Figure 1. Comparison of grading curves: model materials and prototype ballast.

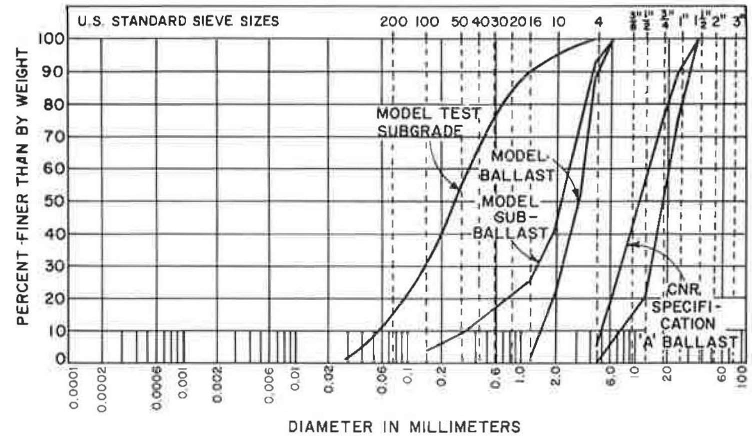
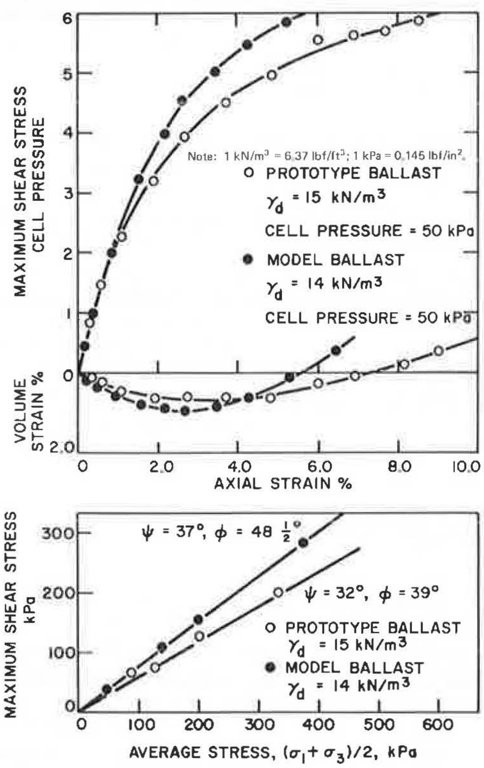


Figure 2. Triaxial test results for ballast.



from the point of load application,

p = applied load at $X = 0$,
K = subgrade modulus (assumed elastic),
$\beta = (K/4EI)^{1/4}$ (where EI = rail-section modulus),
σ_{max} = maximum contact stress between tie and ballast,
S = tie spacing, and
A = area of contact between tie and ballast.

To provide similitude in the forms of the deflection curves and maintain the linear scale for tie spacings, the values of βX must be similar for model and prototype; thus

$$\lambda_\beta = 1/\lambda_L \tag{3a}$$

and

$$\lambda_K/\lambda_{EI} = 1/\lambda_L^4 \tag{3b}$$

where

λ_β = scale factor for the value of β,
λ_L = linear scale factor,
λ_K = scale factor for the subgrade modulus, and
λ_{EI} = scale factor for the rail-section modulus.

The contact stress and the factor of safety against bearing-capacity failure of individual ties must now be considered. To provide the same contact stress in model and prototype, Equations 2 and 3 give

$$\lambda_p = \lambda_L^2 \tag{4}$$

where λ_p = scale factor for the applied load.

The factor of safety of a footing on a purely frictional soil is

$$F = (\gamma/2)\,N_\gamma B/\sigma_{max} \tag{5}$$

where

γ = unit weight of the material (ballast),
N_γ = bearing-capacity factor, and
B = footing (tie) width.

To provide the same value of F in the prototype and in a model using a model ballast of the same density, the stress scale factor (λ_σ) is given by Equation 6.

$$\lambda_\sigma = \lambda_N\lambda_L \tag{6}$$

where λ_N = scale factor for the bearing-capacity factor N_γ. From Equations 4 and 6,

$$\lambda_\sigma = \lambda_p/\lambda_L^2 = \text{unity} \tag{7a}$$

and

$$\lambda_N = 1/\lambda_L \tag{7b}$$

It is theoretically possible to obtain the correct model ballast density that satisfies Equation 7 by using strength data from tests at various densities, together with standard design graphs relating N_γ and ϕ. In practice, this may be quite difficult.

Equation 1 gives model displacements at a scale of

$$\lambda_y = \lambda_p\lambda_\beta/\lambda_K = \lambda_L/\lambda_K \tag{8}$$

The accuracy to which model displacement measurements should be determined can be estimated from Equa-

Table 1. Scaling factors used for model studies.

Item	Prototype	Model	Scaling Factor
Rail-section			
Designation	RE 100	RE 100/6	
Moment of inertia (m^4)	2.04×10^{-5}	1.57×10^{-2}	$\lambda_{EI} = 1296^a$
Rail length (m)	10.97	1.83	$\lambda_L = 6^b$
Tie section (cm wide × cm deep)	23 × 20	3.8 × 3.4	$\lambda_L = 6^b$
Tie spacing (cm)	51-91	8.5-15.0	$\lambda_L = 6^b$
Axle load (kN)	267	7.42	$\lambda_P = 36^c$
Ballast depth (cm)	30	5	$\lambda_L = 6^b$
Subballast depth (cm)	30	5	$\lambda_L = 6^b$
Subgrade depth (cm)	75	13	$\lambda_L = 6^b$
Ballast strength (angle of internal friction) (°)	40	50	$\lambda_N \doteq 1/3^d$
Subgrade modulus (kPa)	15 000	15 000	$\lambda_K = 1^e$

Note: 1 m^4 = 2.41×10^6 in^4; 1 m = 3.28 ft; 1 cm = 0.39 in; 1 kN = 225 lbf; 1 kPa = 0.145 lbf/in^2.
[a] From Equation 3.
[b] Selected.
[c] To give $\lambda_\sigma = 1$.
[d] From design graphs of ϕ versus N_γ.
[e] From Figure 2: $K = E/(1 - \nu^2)$.

Figure 3. Track structure.

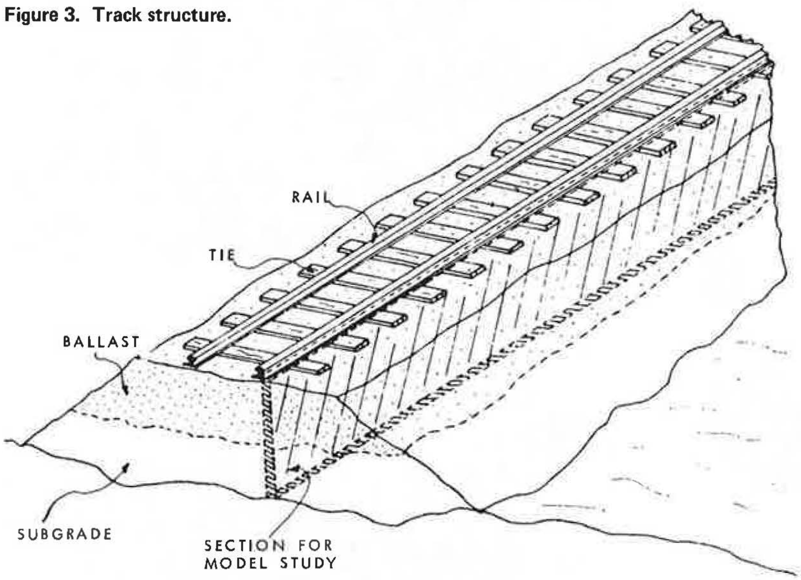
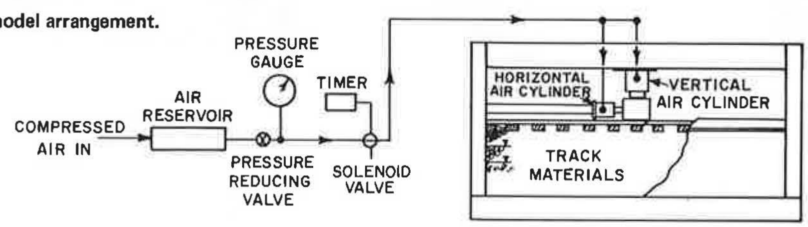


Figure 4. Schematic view of model arrangement.



tion 8. The subgrade modulus (K) is known to increase with increased density of the ballast. To satisfy Equation 7, the model subgrade modulus (λ_K) must be <1 and the accuracy of model displacement measurements will have to be increased. If similarity of model and prototype ϕ-values are maintained (hence, $\lambda_N = \lambda_K = 1$), Equation 6 can be satisfied by $\lambda_\sigma = \lambda_L$, $\lambda_P = \lambda_L^3$ and the model displacements would be expected to develop at a scale of $\lambda_y = \lambda_L^2$ (which would require extremely accurate measurement techniques). Reduced contact stress, in this case, might also create modeling problems, particularly because the behavior in the prototype situation is not elastic and the loadings are not static. Maintaining similarity of both density and contact stress is indicated by the general observation that continued permanent deformation in granular soils under repeated loadings is dependent, mainly, on the initial density and applied stress level (4). Because the deformation of soils is nonlinear, the subgrade modulus will decrease as the factor of safety is decreased. By using a safety-factor scale (λ_F) of >1, it would be possible to make $\lambda_K = \lambda_L$, so that Equation 8 will give $\lambda_y = 1$ (model deformations equal to prototype deformations), which reduces the accuracy required in model measurements. It is estimated that the bearing-capacity factor of safety in the prototype case is about 8-10 and that a similar deformation could be obtained by using a model factor of safety of ≅ 4. Thus, the best approach to physical modeling appears to be to maintain similarity in contact stress level and ballast density by using a model-scale large enough so that the safety factor against bearing capacity is ≥3-4. It would then appear to be of little significance that Equation 6 would, in general, not be satisfied. A single bearing-capacity test on a model tie would provide the additional data needed to determine λ_K.

When λ_K is determined, the rail-section modulus can be designed according to Equation 3.

MODEL TESTS

To demonstrate the practical use of model studies of track support systems, model materials (Figures 1 and 2) were prepared and two-dimensional models were tested by using a linear scale, $\lambda_L = 6$, and the scale factors given in Table 1.

Various tie shapes and tie spacings were tested. Figure 3 shows the longitudinal track section modeled, although the model width was arbitrarily chosen as 0.18 m and the contact stress was appropriately adjusted. Rectangular, round, and wedge-shaped tie sections were tested at three different spacings—$1/\lambda_L$, $1.4/\lambda_L$, and $1.8/\lambda_L$ times the normal prototype spacings; between 11 and 20 ties were included in each test; and the model wheel load was applied directly over the central tie. A horizontal load of 4 percent of the vertical load was also applied (to represent wheel traction) and both loadings were cycled, simultaneously, by using the system shown in Figure 4. The physical model and the loading pattern are shown in Figures 5 and 6, respectively. Figure 7 shows a closer view of the test section; dial gauges were used to monitor the rail deformation under static load and after 10^m loading cycles, where m = 0:1:5. Photographic techniques were used to measure tie-soffit settlements and internal deformations at the same intervals of repeated loadings. Two methods for monitoring internal deformations were tested, and the method (Figure 7) of placing 2-mm diameter rods in the profile was adopted. By using stecometer analysis of photographic negatives, an accuracy of ±0.04 mm in the measured rod movements was obtained (95 percent confidence limit). [Details of test preparation and measurement techniques are given by Pak (6).]

Figure 5. Model test: round ties.

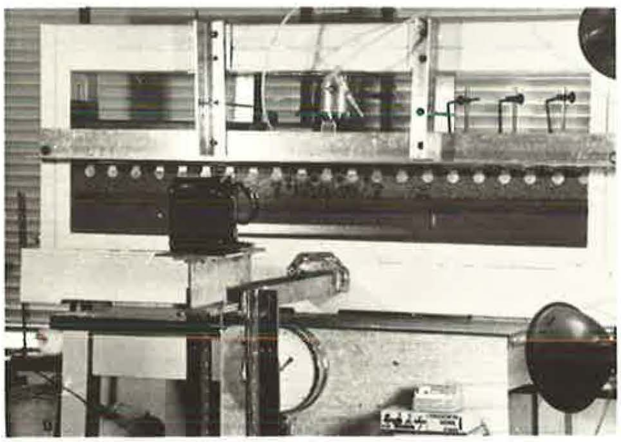


Figure 6. Form of pressure variation in air cylinders (frequency = 1 Hz).

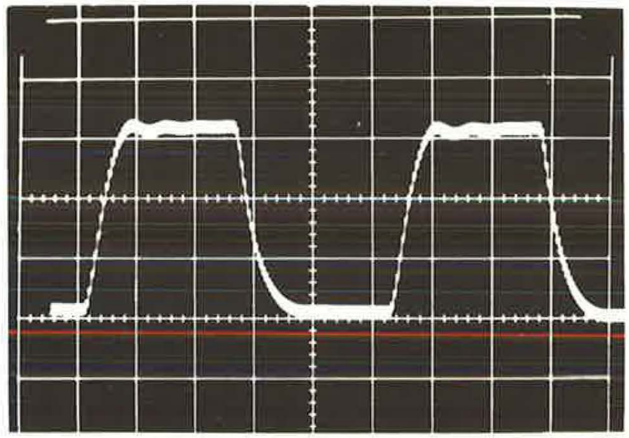


Figure 7. Close-up view of test section that has wedge-shaped ties.

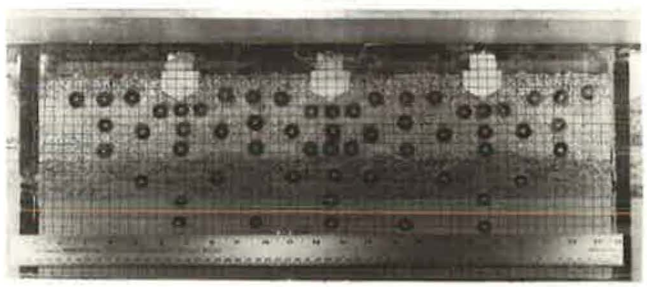
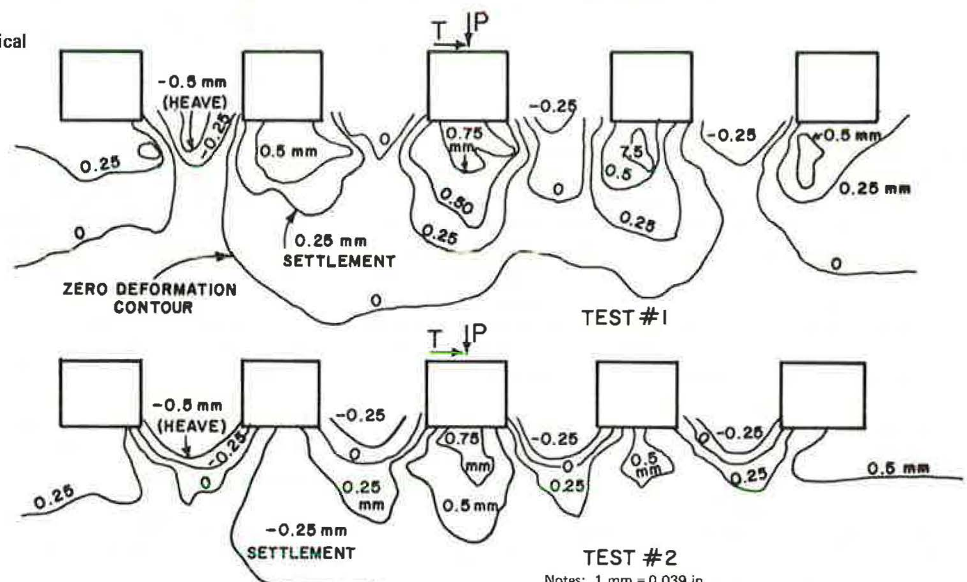


Figure 8. Maximum vertical deformation contours of two identical tests.

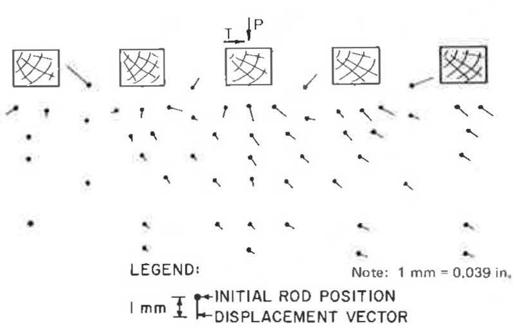


Notes: 1 mm = 0.039 in.
Contour interval = 0.25 mm; 10^5 loading cycles.

MODEL TEST RESULTS

Stecometer readings from the photographic plates were analyzed and plotted by using a computer program. The results of two similar tests are compared in Figure 8 to demonstrate the reproducibility of the test data. Figure 9 shows the rod-displacement vectors for test 2 in Figure 8, and it is noted that small longitudinal displacements developed due to the applied longitudinal load. Figure 10 shows the effect of increasing the tie spacings. By considering the displacements of the rods at the corners of triangular elements, the volume changes in the supporting soils can be calculated (see Figure 11); the dilation (volume increase) of ballast between the ties is quite apparent. The results for the other two tie shapes were quite similar although, as can be seen by comparing Figure 12 with Figure 9, the wedge shape reduced the lateral displacements and the intertie dilation while slightly increasing the vertical displacements. The wedge-shaped and circular tie soffit shapes exhibited marginally superior performance at the larger tie spacings, but the rectangular ties exhibited the least amount of vertical deformation at the conventional spacing. Figure 13 shows, typically, how deformation developed with the number of repeated loadings and that continued inelastic deformation does develop. A direct comparison of the data in Figure 13 indicates that there was little variation among the various tie shapes but that tie spacing is an important consideration. The data indicate that ties should be placed as closely as the practical limitations of economics and compaction methods will allow.

Figure 9. Movement of rods after 10^5 cycles of repeated loading: rectangular ties at 85-mm center-to-center spacing.



Alternatively, the bearing area of each tie could be increased at the same tie spacing.

Foundation subgrade moduli were calculated by using dial-gauge readings taken from the first loading applied after track preparation and compaction. Two methods were used: the first involved a summation of the deflections at all ties in the form

$$K = P/S\sum_{i=1}^{N} y_i \tag{9}$$

where y_i = deflection ordinates of the rail, measured at all N tie locations.

The second method used only the deflection at the center tie (y_o) and is given as

$$K = p\beta/2y_o \tag{10}$$

The results are shown in Figure 14. The first method gave moduli of 1.5-3 times that of the second method, and the rectangular ties consistently gave lower moduli. In theory, this modulus reflects the integrity of the track foundation; in practice, the modulus is largely dependent, for a given tie size and spacing, on the compaction conditions directly beneath the ties. Compaction around and under the ties was carried out, in the model, by using curved steel probing rods to simulate prototype compaction methods. Because the performance of the rectangular ties was essentially similar to that of the other shapes, the lower moduli for the rectangular shape are attributed, mainly, to the greater difficulty in achieving good compaction under this shape. (Other workers have also concluded that compaction under rectangular ties is difficult.) Thus, the rectangular ties might have proved superior if it were not for the negative effect of the compaction problem. The difference between the two methods of moduli determination is considered to be due to the inelastic nature of the geotechnical support media and to the fact that the model rail system was the finite length. It therefore appears that the second method (that using Equation 10) gives the best relative values of moduli for model test analysis. The usefulness of model studies based on the beam-on-elastic-foundation approach is considered to be supported by the fact that Equations 9 and 10 gave moduli values that were of the same order of magnitude.

Figure 10. Vertical deformation contours of tests with rectangular ties.

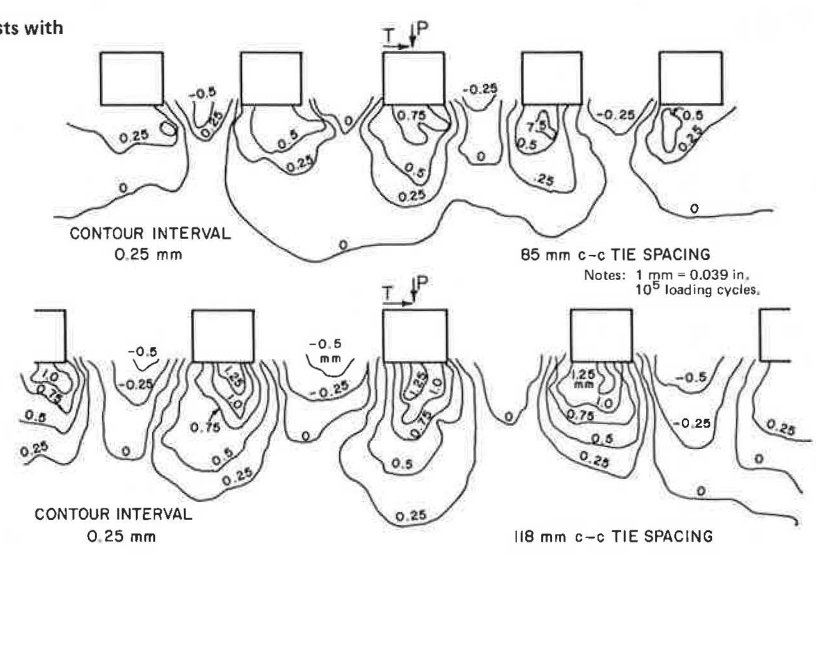


Figure 11. Volumetric strain in various zones after 10^5 loading cycles: rectangular ties at 85-mm center-to-center spacing.

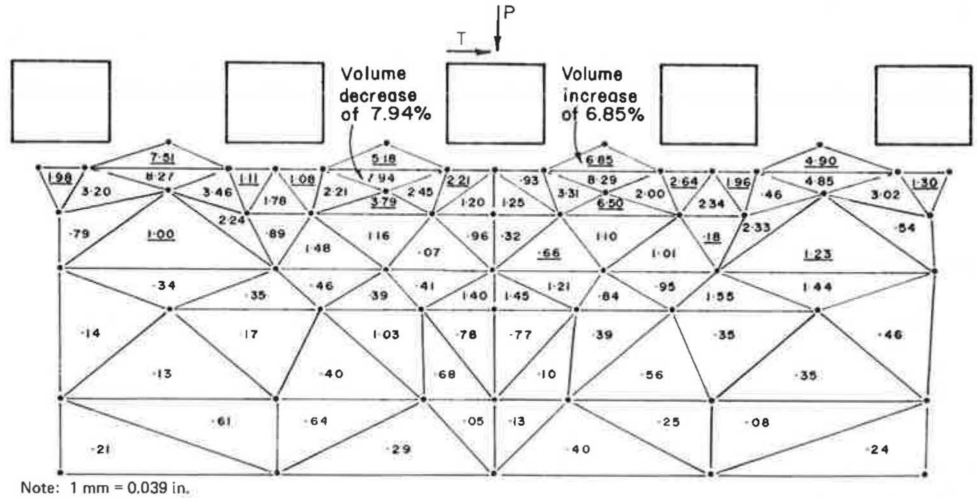


Figure 12. Movement of rods after 10^5 cycles of repeated loading: wedge-shaped ties at 85-mm center-to-center spacing.

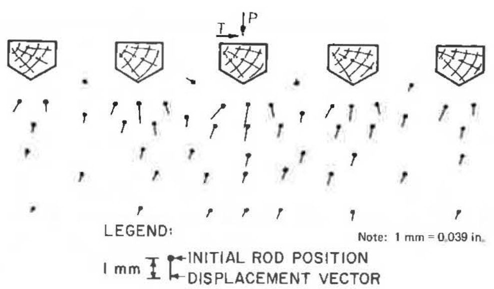


Figure 13. Vertical deformation of ballast: 85- and 118-mm spacing.

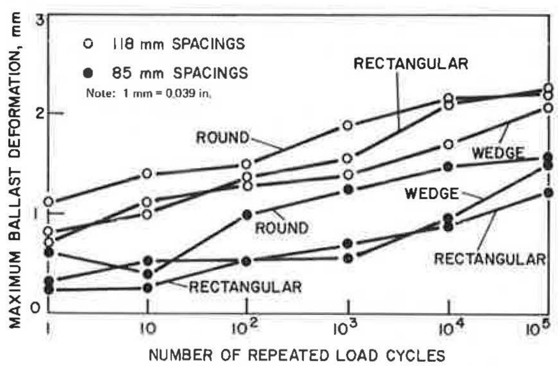
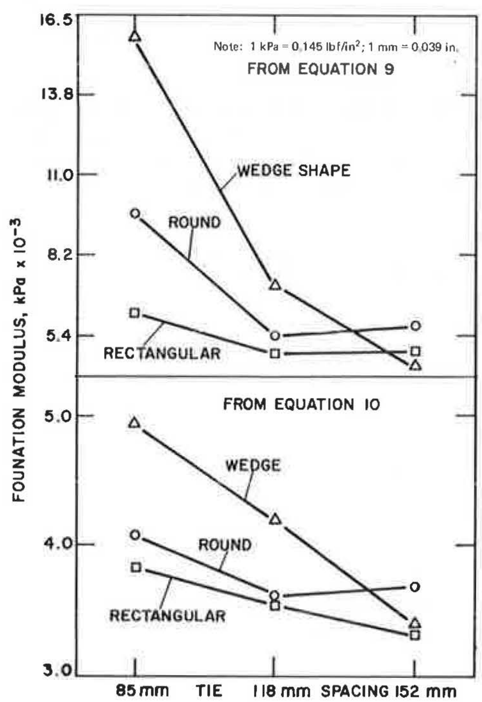


Figure 14. Calculated foundation moduli.

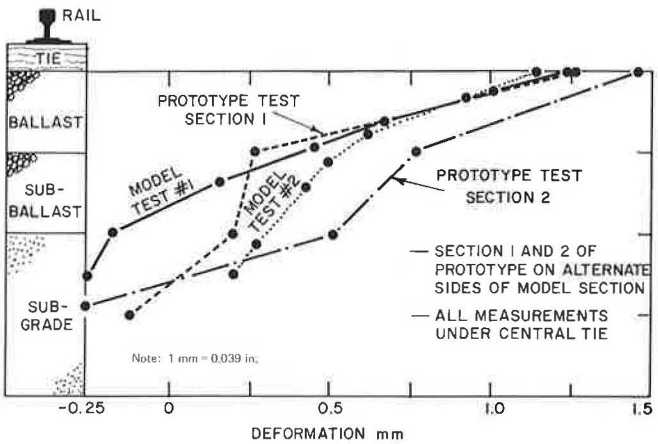


COMPARISON OF MODEL TESTING WITH PROTOTYPE TESTING

To compare the results with prototype behavior, the scaling factors must be compared with the prototype. Raymond and others (3) have published the results of a full-scale test section of limited length (11 ties) loaded at the central tie by a simulated, repeated axle load. The full-scale section used a 66-kg/m (132-lb/yd) RE rail section having a moment of inertia of $3.67 \times 10^{-5}\,m^4$ ($88\ in^4$) and the conventional tie spacing of 0.23 m (9 in). From Equation 10, the prototype subgrade reaction was found to be 14 680 kPa (2129 lbf/in^2) compared with the model value of 3860 kPa (560 lbf/in^2) (Figure 14). The scaling factors are then $\lambda_{EI} = 2338$ and $\lambda_K = 3.8$. The remaining factors are the same as given in Table 1 and, because the system is relatively flexible [i.e., $(KL^4/4EI)^{1/4} >> \pi$], the differences in subgrade moduli would not alter the contact stresses under the loaded ties significantly. The value of λ_β is then given as $(\lambda_K/\lambda_{EI})^{1/4} = 16.25 \times 10^{-4} = 0.2$, which is close to the ideal value of 0.16 given by Equation 3. The factor of safety scale is calculated by using Equations 5 and 6 as $\lambda_F = \lambda_N\lambda_L/\lambda_\sigma = 2$, and the deflection scale is given by Equation 8 as $\lambda_y = 1.89 \doteq 2$.

Thus, the model displacements should be about 50 percent of the prototype displacements. Figure 15 shows that the model deformations are of the same magnitude as the prototype and that reasonably good correlation is obtained between model and prototype deformations. The deviation between the calculated displacement factor of 2 and the observed deformation factor of 1 is considered to be due to the nonlinearity of the load-deformation characteristics and the differences in bearing-capacity safety factors. Because the safety factor of the model is

Figure 15. Comparison of model and full-scale foundation deformation: 10^5 loading cycles.



only 50 percent of that existing in the prototype, the deformations in the model are about twice those expected. It may be concluded that the beam-on-elastic-foundation approach, as described above, is quite suitable for designing models of track support systems. Despite the lack of exact similitude, it is concluded that models, down to one-sixth of the prototype size, are suitable for comparison of the effects of varying system components.

Pak (6) has reported 10 model tests that were carried out in a five-month testing period. The full-scale test conducted by Raymond and others required more than six months. A field-test program carried out over a two-year period on eight test sections of a main-line track and reported by the Association of American Railroads Research Center (7) arrived at many conclusions similar to those found in the model studies described here. In addition to the direct cost savings, the size and cost of associated laboratory testing equipment are proportionally reduced when model-scale materials are used.

MODEL SCALES, TEST VARIABLES, AND MODEL FACILITIES

As described above, the linear scale-reduction factor (λ_L) is limited by the ballast-size distribution to about 6. Internal instrumentation must be miniaturized to reduce interference but, because loads and deformations are reduced in the ideal model, the problems of instrumentation should be similar at both model and prototype scales. Because of the large number of potential test variables, a model test facility should be designed to be as versatile as possible, even to the extent of using models of prototype compaction devices for preparing tests. Considering the relationships discussed in this paper and the behavior of soils materials, a model scale factor of $\lambda_L = 5$ would probably be most suitable. A 250-kN (56 250-lbf) prototype axle load would then become a 10-kN (2250-lbf) model axle load. For such reduced loads, it would be feasible to design and construct a real model facility that incorporated mobile, rather than fixed, repeated loads (air or hydraulic loading cylinders mobilized between a fixed overhead-guidance rail and model railway cars). A real model facility would, of course, provide increased testing capabilities, including wear testing on model rails and rolling stock.

Approximate models that use fixed repeated loadings are appropriate for basic study of the track system variables. Optimization of ballast grading and depth, rail stiffness, and tie size and spacing for various track requirements (loads, speeds, traffic density, deceleration sections, and such) is one area for potential studies. The tests reported in this study indicate that the present prototype system is not well suited to resisting longitudinal traction forces (as would occur during deceleration). Intuitively, the lack of lateral confinement in the ballast and subballast layers appears to be a possible reason for continued settlements despite efforts to achieve optimal compaction of these layers. Possible methods of increasing lateral confinement by earth reinforcement techniques could be studied economically at a suitable model scale.

SUMMARY AND CONCLUSIONS

The primary purpose of this paper is to demonstrate the capabilities and usefulness of model studies for evaluating the performance of track support systems. The following general conclusions are noted:

1. The beam-on-elastic-foundation theory can be used to evaluate model similitude providing that the nonlinear behavior of the soil materials and the bearing capacity are adequately considered. Data for correlation with theoretical predictions or for predicting prototype behavior can be obtained from model studies.
2. Model studies are efficient and can be extended to evaluate factors or systems that would involve excessive costs if evaluated at the prototype size. Indeed, a real rolling-stock model is considered practical at a linear scale factor of about 5.

The model studies reported in this paper indicate that, for a given load, reducing the tie spacing will reduce settlements. Of the three tie shapes tested, the rectangular-shaped ties were, at normal spacing, superior in resisting vertical settlements, although a simple wedge shape was superior in resisting longitudinal loads and also performed better at larger tie spacings. The model studies also indicated that, except for the advantage of better resistance to longitudinal loads, no gain is realized by divergence from the normal rectangular shape. Tie-size variations were not investigated. The behavior in the model tests under repeated loading was found to be reproducible and correlated well with the observations made in a prototype scale test.

ACKNOWLEDGMENT

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Railroad-Highway Grade-Crossing Analysis and Design

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This paper presents a computerized design system for a highway-railroad grade-crossing foundation. The design criterion used is the permanent differential deformation between the railroad track and the adjacent highway pavement. This design criterion is related to two performance criteria: dynamic-load profile and roughness index (which is a measure of the ride roughness experienced by a vehicle passing over the grade crossing). The effect of the permanent differential deformation on increasing highway dynamic load is included in the computer program, as is the increase in dynamic railway wheel loads. Characteristic properties of materials, including the effects of environmental factors (such as temperature and suction), on subgrade material properties are considered. The computer program calculates the permanent differential deformation (the design criterion) caused by repetitive wheel loads during a design period for both highway and railway traffic. The number of wheel-load repetitions (to serve a design period) for highway and railway traffic are considered separately in the calculations; therefore, this design system can handle any combination of high and low volumes in railway and highway traffic. Design examples are included.

Highway-railroad grade crossings are a subject of continuing concern because of the maintenance problems caused by load-associated roughness. The magnitude of dynamic highway loads over a grade crossing increases with time as the pavement on each side of the crossing becomes distressed because of the repeated loads. The relative permanent deformation between track and pavement determines, to a large extent, the degree of roughness experienced by passing traffic. Therefore, the material properties (such as resilient modulus and permanent strain) of grade-crossing materials are important in design.

Length of trains, weight of rail cars and locomotives, and speed contribute to failures of track structures and crossings. Railroads are also concerned with ridability and operation of trains at grade crossings.

PRESENT STATUS

There are more than 200 000 public grade crossings in the United States. Surface materials include timber, bituminous pavements, concrete slabs, rubber panels, metal sections, and others. It is clear that, regardless of the type of surface material, the proper design of track structure, base, and subgrade materials (including adequate drainage) determines the performance and life of a grade crossing (1).

Committee 9 (highways) of the American Railway Engineering Association has published reports on the merits and economics of various types of grade-crossing surfaces. However, this literature does not provide information for grade-crossing-foundation design. Important characteristics such as (a) the influence of crossing profile (roughness characteristics) and highway-vehicle speeds on dynamic loads at the crossing and its approaches; (b) the interactions between individual physical and geometrical characteristics of the grade crossing; and (c) the stresses and deformation in ballast, base, and subgrade, due to both highway and railway loadings and their dynamic effects, are not well defined.

The performance of a grade crossing is measured by three performance criteria:

1. Dynamic-load profile,
2. Roughness index, and
3. Permanent differential deformation.

These criteria are related to each other; i.e., an increase in one will increase the other two. The application of loads on a grade crossing causes the track structure and the adjacent pavement to deform differentially. This difference in deformation is due to the differences in material properties, loading, and thickness of the two structures.

Permanent deformation is a function of the level of stresses at varying depths produced by the size of the applied loads, the number of load applications, material properties, and environmental factors such as temperature and moisture balance.

This paper describes a design procedure that includes all of these effects and a computer program that was developed to calculate the necessary parameters.

DEVELOPMENT OF DESIGN PROCEDURE

The design procedure is divided into three phases:

1. Fixing the required dimensions and geometry of the grade crossing,
2. Selecting the materials for foundation layers (emphasizing the effects of environmental factors such as temperature, moisture balance, and drainage on the properties of these materials), and
3. Establishing design criteria and acceptable limits to control the design system.

Design Criteria

Three design criteria are considered: (a) dynamic-load profile, (b) roughness index, and (c) permanent differential deformation between track and adjacent pavement.