concrete ties will not be made for several years, they appear to be performing as intended. The ties on the NEC have, during the last 4 years, provided good track geometry retention while being subjected to up to 82 million gross tons in addition to 110 mph passenger operations.

Amtrak is continuing the evolutionary development of the specifications and maintenance technology associated with concrete ties with an eye toward additional installations in the future. Funding is currently being sought to complete the installation of concrete ties on two tracks between Washington, D.C. and New York. Also, the satisfactory performance of the concrete tie has led to the exploration of the feasibility of concrete switch ties. Amtrak remains firmly committed to the development of the concrete tie and urges others to write for more information about its experience.

REFERENCES

1. De Leuw, Cather/Parsons. Northeast Corridor Improvement Project: Task 202: Concrete Tie Cost and Performance for Track Structures. FRA, F202-37, Oct. 1977.
2. Northeast Corridor Improvement Project: Redirection Study. U.S. Department of Transportation, Jan. 1979.
3. De Leuw, Cather/Parsons; STV Engineers, Inc. Northeast Corridor High Speed Rail Passenger Service Improvement Study: Task 3--Track and Structures Upgrading Standards Development. FRA, FRA-ONECD-75-3, Sept. 1975.

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Geotechnical Evaluation of Track Structure

W.S. STOKELY AND W.T. McNUTT

The Illinois Central Gulf Railroad undertook a program of track roadbed stabilization as part of a track rehabilitation project financed by FRA's purchase of preferenced shares under Title 505 of the Railroad Revitalization and Regulatory Reform Act of 1976. The investigation and analytical techniques that evolved from these projects are summarized in this paper. The procedure of data gathering used to identify and classify observed irregularities in track surface geometry is described. Also described is a method of field investigation to prove theories of failure developed by study of the collected data. The laboratory analysis of soil samples recovered from sites selected for remedial measure and the methods employed to achieve enhanced track roadbed strength are also addressed.

Addressed in this paper is a method of geotechnical investigation developed during a program of roadbed rehabilitation performed in three successive stages on the Illinois Central Gulf (ICG) railroad. The program was funded by FRA's purchase of preference shares as provided for in Section 505 of the Railroad Revitalization and Regulatory Reforms Act of 1976. These resurfacing, restoration, rehabilitation, and reconstruction (4-R) stages of the program, which were primarily track superstructure rehabilitation projects, were begun in the fall of 1977 and completed in April 1983.

SYSTEM

The manner in which the 4-R programs were organized provided a means of segmenting the 700 route-miles of track into more manageable lengths. A segment lends itself to logical analysis of the results of remedial expenditures and, preferably, has beginning and ending points pertinent to train operations.

The system also required a method of investigation. The method evolved into a two-part program. The first part is the initial investigation, which results in a report of site selection. The second part is the detailed investigation, which results in a recommendation of remedial work.

Of primary importance to any system is the recognition of a goal. The goals of this effort are (a) to determine the time-dependent response of the plane of the top of the rails to germane force fields and (b) to evaluate the probable increase of the length of a track surface maintenance cycle by installing a designed remedial measure. The system must also recognize that track that can be maintained to the requirements of service and regulation without an extraordinary expenditure of track maintenance resources, as determined by the responsible maintenance officer of the company, is good track and not a fit subject for these procedures.

INITIAL INVESTIGATION

The initial investigation is the crux of the roadbed stabilization effort. It consists of three activities: office investigation, field observation, and site selection. The office investigation consists of the collection of segment history, geometry, topography, and climatological and geologicl data. The field observation consists of an on-track inspection in the company of maintenance officers familiar with the segment. Site selection, the formal results of the initial investigation work, lists and sets the priority order for the lengths of track in a segment that has track surface irregularities and notes the sites to be included in the detailed investigation.

Office Investigation

The purpose of the office investigation is to gain insight into the lay of a segment of track and its environment. This study has two results. The first and most important is to enhance the investigator's knowledge of the segment, and thus increase understanding during the field investigation activity. The second result is to broaden the data available for a segment, and thus enhance site-selection reporting.

Field Observation

Successful gathering of field notes is the key to a successful initial investigation effort. A day of work will require the efforts of three people: the investigator, the person having first line responsibility for the maintenance of the track to be observed, and the immediate superior of the maintenance person.

The work day is divided into three phases: the briefing, the on-track trip, and the debriefing. The briefing is to be conducted by the investigator during an early morning breakfast. It consists of a discussion of the details developed in the office investigation for the track to be covered that day, a statement of the data to be gathered, and a review of the terminology to be used in the log of the trip. The on-track trip is to be made by using a hi-rail inspection vehicle, equipped and supplied in accordance with the rules of the company. If not a part of the rules for on-track operation, a timetable governing the track to be ridden and a set of train orders for a train that is to run or has run on the day of the trip are to be furnished. A schematic track plan is also necessary. The investigator is to supply blank forms of the log of inspection.

The trip should begin at the lower numbered milepost and be continuous with respect to mileposts. The investigator is responsible for maintaining the log of inspection. All aboard are required to observe and call out irregularities in the track and roadbed. An inspection team can be expected to log 50 to 75 miles of track per day under most conditions. In general, dismounting during the trip is not required; however, it is not to be discouraged.

The debriefing session should take place in a relaxed atmosphere. It should consist of a general discussion of the day's trip. The formal activity of the debriefing is to order the priority of the sites noted in the day's log. The junior maintenance officer is to note the five most troublesome sites and rank them 1 through 5, with 1 being the most troublesome.

Throughout these activities, the investigator must be attentive and encourage feedback from the maintenance officers. Rapport within the investigation team is of primary concern. The investigator is generally an outsider and must gain acceptance or the effort will achieve only minimum results.

Log of Inspection

Because the field inspection trip is the most important activity of the initial investigation, the log of inspection is a primary document. The headings in the log, other than the administrative data, should be location, description, length, maintenance cycle, speed, and classification level.

The location of a site is recorded by its milepost location to the tenth of a mile. The description heading notes the defect. The length of a site is to be recorded in a convenient measure. A longer site is usually noted in tenths of a mile and shorter sites are noted as a number of rail lengths.

The maintenance cycle data are furnished by the junior maintenance officer and are an on-the-spot estimate of the length of time between corrections to the surface of the track. The current permissible speed is determined from timetable and train order data. The speed data are best entered during the debriefing session.

The most important entry in the log is the classification level. Under this column the investigator, in conjunction with the maintenance officers, assigns a ranking of the results of usual maintenance procedures. Level 1 indicates a track surface irregularity that requires frequent or long duration slow orders and that, in the opinion of the maintenance officer, does not respond to the usual surface correction procedures. Often the maintenance officer will use the term chronic.

Level 2 indicates a track surface irregularity that requires periodic slow orders and that, in the opinion of the maintenance officer, responds only marginally to the usual surface correction procedures. These sites are often discussed in terms of being chronic during certain times of the year. Level 3 indicates a track surface irregularity that will generally not result in a slow order of significant speed reduction and that, in the opinion of the maintenance officer, responds adequately to the usual surface correction procedures. Note that level 3 allows the investigator to record every irregularity of track observed during the on-track inspection, including those that respond to the usual maintenance methods. Experience has shown that sites marked as levels 2 and 3 will, in subsequent reviews, tend to change categories both up and down the scale.

The letter S may be added to any classification level. It denotes a site that raises a question of safe operation in the mind of the investigator based on experience with irregularities of section geometry or soil conditions. A site that raises a question of safety in the mind of the maintenance officer must be dealt with immediately.

The entry in the description column is complex from a geotechnical standpoint and is the first assessment of the defect. Development of a standard nomenclature is important for uniform identification of roadbed defects. Many of the terms can be self-explanatory, such as blocked drainage account cut slope erosion; short shoulder account end of culvert failure; and other descriptions that entirely define the problem.

Four phenomena are readily identified by noting track movement: track squeeze, shoulder slide, through track slide, and ballast slides. The signs of track squeeze (Figure 1) are the loss of alignment and cross level to the same side, the apparent ballast crowning to the side of the failure, and the apparent filling of the ditch in a cut section or the raising of the shoulder in a fill section.

The shoulder slide (Figure 2) is an embankment section failure. It has many of the signs of a track squeeze, except the roadbed shoulder is depressed instead of raised.

A through track slide (Figure 3) can occur in a cut section and, except for the direction of alignment change, it has many of the same signs as a track squeeze. This defect is usually an embankment section failure and is characterized by alignment change away from the loss of cross level, some shoulder crowning at the extreme edge of the shoulder, and of course, the bulged slope.

The ballast slide (Figure 4) is more often found at a derailment site. It has the characteristics of shoulder slide, except only the width of the ballast shoulder is involved in the movement.

In general, these four modes of failure are not sudden but are characterized by increasing rates of movement. The maintenance officer measures the increased rate by noting the decreased time between track surface adjustments.

A fifth failure mode is more difficult to recognize and it is a sudden failure of the track supporting structure. The top of fill wash-out (Figure 5) is characterized by a track subsistence, usually with a loss of cross-level, and the development of a bulge in the slope, usually with tension cracks on the top of roadbed shoulder or on the face of the slope. The mechanism of failure is hydrostatic pressure in the ballast pocket that, when applying force to the slope soils, also reduces soil shear strength by elevating its moisture content. Sudden

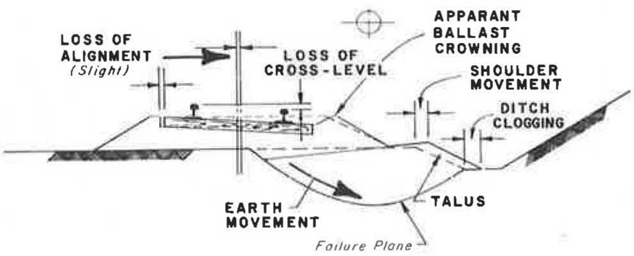


Figure 1. Track squeeze.

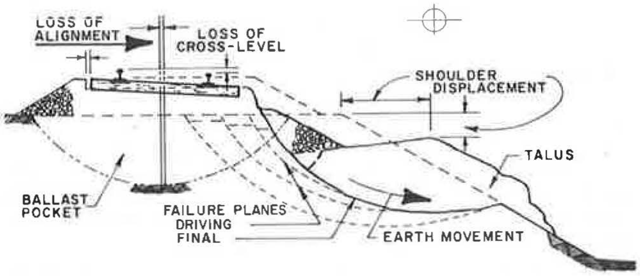


Figure 2. Shoulder slide.

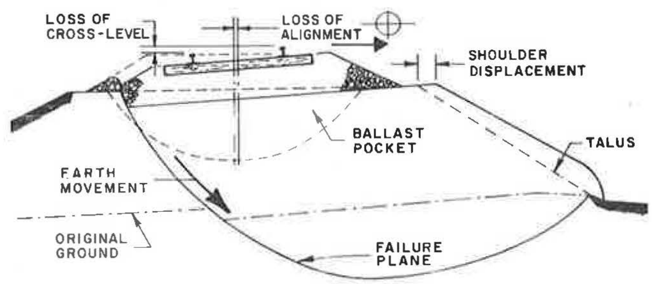


Figure 3. Through track slide.

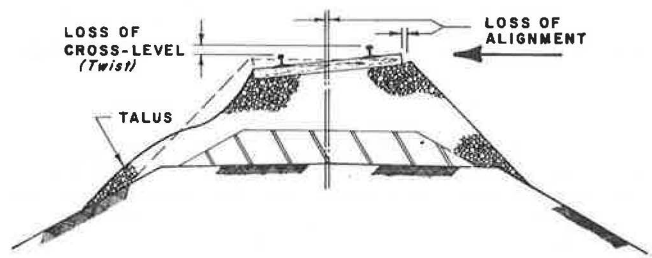


Figure 4. Ballast slide.

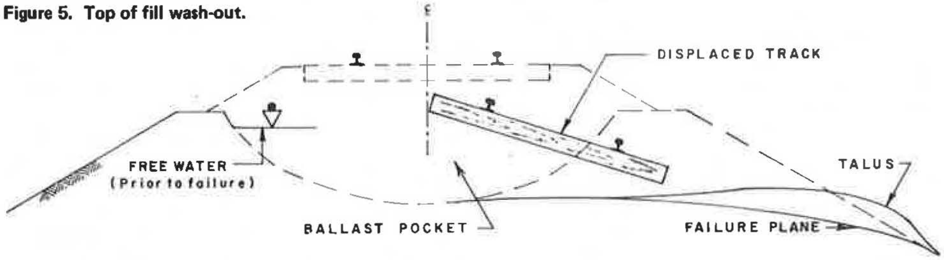


Figure 5. Top of fill wash-out.

failure occurs when the side slope can no longer resist the hydrostatic pressure. The resultant wash-out flows over not only the side slope soils but also over the materials of the ballast pocket and the ballast section. The mechanics of the failure are such that it will probably occur in an unloaded track condition.

The investigator also records data under the description entry that relates to weather and the length of maintenance cycle. The question, "Does the track surface maintenance cycle increase with the wet season or the dry season?" is asked, and the response is recorded.

For a site to be detected the investigator (as well as the entire inspection party) must recognize clues. The primary clues are ballast neat line and roadbed shoulder line regularity, track alignment, cross-level and profile accuracy, and indicators of recent work. Line regularities are visual clues. Track accuracy clues are visual and can be felt in a moving vehicle. An indicator of recent work would be a scant ballast section caused by surface adjustment by using ballast gathered at or near the site. A track full of ballast would indicate that work is anticipated. A change in ballast color may indicate recently placed and worked ballast.

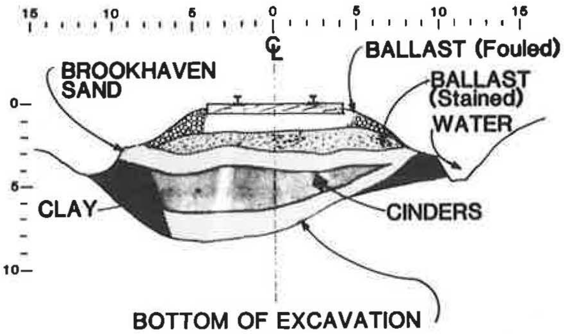
Site Selection

With the completion of the field observation activity, data gathering is complete and the investigator is ready to produce the report of site selection, which contains two parts: the log of inspection and the list of selected sites. The list of selected sites contains a summary of available data on the sites and provides a first estimate of costs of remedial measures at each site. Site selection is governed by three principles. The first principle is safety; any site that is questioned as to safety must be included as a selected site. The second principle is efficiency of train operation. The site or group of sites that is farther removed from other sites would be considered in order to provide the longest possible length of timetable speed operation. Sites that are attended by more difficult train-handling characteristics such as on grades and in curves would be considered in order to reduce instances of stalls or derailment caused by train dynamics. The third principle is adherence to established budgetary constraints. This principle may require that a segment as defined for investigation be redefined to include less length. If this is the case, the three principles are then applied to the redefined segment, and the required segment shorting is brought to the attention of the officer in charge. A shortened segment must not exclude a site classified with the S, safety, suffix.

DETAILED INVESTIGATION

The purpose of the detailed investigation is to develop a remedial action. The procedure is to develop a theory of failure for each of the sites to be considered and then to prove or disprove the

Figure 6. Plot of ballast pocket stratification.



theory. The process of proving a theory will, to a large extent, dictate the appropriate remedial measure. Testing that disproves a first theory will lead the investigator to a more correct theory, and therefore, to the appropriate remedial measure.

The detailed investigation of a selected site begins with an on-the-ground inspection by the investigator and has two purposes. The first purpose is to develop the theory of failure; the second is to determine the actual length of the defect in the field.

When the site defect and length are defined, field exploration is ordered. The tools of exploration are field survey, subsurface soil sampling, and the track cross-trench. The field survey employs usual techniques to determine pertinent site topographic detail. The cross-trench excavation with the plot of ballast pocket stratification (Figure 6) is the primary soils exploration tool. A hi-rail-mounted drill rig, unique in that the derrick and machinery are mounted on a turntable that permits hollow stem auger boring and sample recovery on the centerline of track and at 5 ft either side of centerline, is used to prove theories that involve depths greater than 12 ft and to explore site foundations.

The finding of all investigations must be collected and cataloged in a manner that enhances the geotechnical data base of the company. A statistically significant random pattern is used to investigate a site. Under this arrangement a site is investigated at six row locations, regardless of the length of the site. Testing in a row is located at a column. Column 1 is the right column as the observer faces the direction of increasing mileposts, column 2 is the center of track, and column 3 is to the left. Row 1 is closer to the observer and row 6 is at the far end of the site.

At each row location a track cross-trench is excavated. Subgrade soil samples are taken on the column lines, and the ballast stratification is plotted. Also, on each column line, pocket penotometer, Torvane shear, and Eley volumeter measurements are taken and recorded.

A minimum of two deep borings are usually taken, one each in rows 1 and 6 for the purpose of discovering the foundation of the site. The depth of these borings in a fill section is set to include approximately 10 ft of the soil below the placed embankment. In a cut section a depth of 25 ft is specified. The down-hole sampling is one thin-walled sampling tube and one split spoon sample per 5 ft of depth. All soil samples are logged and handled in the usual manner.

Laboratory Analysis

The laboratory analysis of the soil samples emphasizes three parameters that relate to track performance. First, free swell testing conducted from air dry to saturation moisture content measures moisture-volume relations. Second, consolidation under repeated load measures the elastic/plastic properties of the soils. Finally, direct shear testing is conducted with two functions being observed. The first is ultimate shear strength. The second is measurement of stresses to produce strains of 0.5 percent.

The data of free swell testing are an indicator of the movements that can be expected because of weather. The repeated load data can be related to railroad traffic, and consolidation characteristics and rates can be evaluated. Finally, direct shear testing points to the likelihood of mass movements and, by using the low strain and railroad traffic data, the creep rate of shear failures can be evaluated.

By comparing data of a test row, track cross-level performance can be evaluated and, by working with data of columns, track profile and twist performance can be evaluated.

Early in the work on ICG pressure injection of designed lime and fly ash slurry was tested as a possible remedial measure. In the laboratory, soil samples are injected with the design slurry and the free swell, repeated load, and direct shear testing performed on these samples. With both untreated and treated sample data, the results of the treatment can be evaluated numerically in terms of untreated sample performance.

Study of the ballast pocket strata plots from the track cross-trench work reveals failure history and defects of construction or maintenance (Figure 7). Consolidation events take on bowled shapes. The depth of the bowl then is an indicator of the extent of movement and, by study of the thicknesses of the different ballasting materials, conclusions can be drawn about the timing of the consolidation events. Shear events are obvious and easily differentiated from consolidation occurrences.

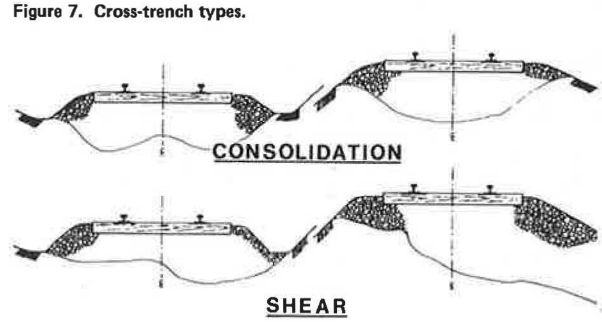
Report of Recommended Remedial Work

The result of the detailed investigation is a report of recommended remedial work. This report details the work to be done to increase the life cycle of track surface maintenance and attempts to evaluate that increase in terms of additional cycle life per unit of track loading. In the case of ICG the unit of track loading was taken as 20 million tons of locomotives, cars, and lading per year.

The method of remedial work most predominant in the ICG work was injection of a designed slurry of lime and fly ash. Roadbed cross-section geometry correction was also an important method. Conventional slide pilings were installed in some safety situations and a permanent measure was taken later.

A range of other methods was also considered. Explosive consolidation, Franke Pile, portland

Figure 7. Cross-trench types.



cement-sand injections, chemical injections, subsurface drainage systems, and even minor relocations of the roadbed were considered. The salient point of all the methods considered was that the work of correction had to be performed under railroad traffic conditions.

CONCLUSION

Geotechnical evaluation of a track structure is to be done on a segment basis. Of the phases and activities of a geotechnical evaluation program, the field observation phase and the log of inspection activity are critical. The track cross-trench exploration tool is the most revealing method.

Collection and organization of a geologic data base is important to a continuing program of track support improvement. Laboratory testing procedures must be directed at specific track performance characteristics. Geotechnical solutions to mass earth movements may be necessary to keep a segment of track open for service; however, geotechnical solutions that address day-to-day track maintenance problems are of increasing importance. These latter problems and their solutions are subtle.

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Constitutive Modeling of Materials in Track Support Structures

C.S. DESAI AND R. JANARDHANAM

Track support structures for railroads and other mass transportation vehicles consist of multicomponent systems. Traditionally, the rail-track support bed includes the rail or guideway, ties, ballast, subballast, and the natural ground or subgrade. Under repeated applications of wheel loads from the vehicles the bed is subjected to complex loading conditions. Furthermore, the materials in the bed and their interactions are complex from a physical viewpoint. Hence, appropriate and comprehensive tests are necessary to define the constitutive or stress-strain behavior of these materials. Advanced testing devices with sophisticated and highly sensitive loading systems and deformation detecting systems are used in this study to perform a number of tests on various materials. These include subgrade soil, subballast, ballast, and wood tie, which are tested by using two truly triaxial or multiaxial testing devices. The tests are performed under different stress paths and densities relevant to the site conditions at the UMTA test section, Transportation Test Center (TTC), Pueblo, Colorado. The materials are subjected to a number of load-unload-reload cycles, and the stress-strain responses are recorded. The responses of the materials are examined carefully and appropriate constitutive laws are developed. A critical state, modified cam clay model is found to simulate behavior of the subgrade soil. Although behavior of the subballast is found to be nonassociative, an elastic-plastic hardening model based on the associative rule is proposed as an approximation. A conventional resilient modulus approach is used for the ballast. A variable moduli model is also proposed as an alternative to account approximately for the inelastic behavior of the ballast. Wood is modeled as an orthotropic elastic material. The foregoing models are cast in forms that can be implemented in solution techniques such as the finite-element procedures. Most of the results reported here can be considered new in the sense that the behavior of the materials in track support structures has been studied perhaps for the first time by using the truly triaxial device in which the field conditions can be simulated and materials can be subjected to three-dimensional stress states. The constitutive models are verified with respect to laboratory tests as well as by implementing them in finite-element procedures. The main objective of this paper is to describe the testing and modeling aspects; the implementation aspect is stated only briefly.

The need for development of mass transportation is acute in this country. Considerable attention is being given to improving the existing railroad systems and to planning and rationalizing the design of new rail track beds to suit the needs of high-speed vehicles. For a complete understanding of the behavior of track support structures, the characteristics of various components of the track beds and their behavior under repetitive loads must be determined.

About 40 percent of the funds spent for the upkeep of track beds in North America is spent on the procurement, distribution, and rehabilitation of ballast (1). About 15 to 20 percent is spent to replace decayed ties and repair spike-torn ties (2). Therefore, the identification of failure and other useful criteria of the materials in the track beds and the relationships between loading environment and foundation material behavior will not only make the analysis of track beds more rational and realistic but can also curtail the maintenance cost.

Furthermore, when numerical schemes such as the finite-element method are used to analyze the track bed, the ultimate effectiveness of the high degree of precision and reliability of this method can be achieved only by the use of valid constitutive relations for the materials under consideration. The accuracy and precision of these relations are governed by the applicability of the constitutive law and the ability to measure true material response in the laboratory. Also, evaluation of the material response under laboratory conditions that simulate the field conditions is highly desirable.

The materials in the track bed are subjected to general three-dimensional states of stress. The loads are repetitive and arise from the wheel loads during travel of a single train. The repetitive loads also arise from the passage of a number of trains over a given section of the track. Thus, the track bed is subjected to a series of loading, unloading, and reloading cycles (3).

Conventional laboratory test equipment is not capable of providing the material parameters that account for the effects of three-dimensional stress fields. Therefore, two truly triaxial testing devices have been used in this investigation. A high-capacity, truly triaxial device of 20,000 psi capacity with a sensitive electrical inductance-type deformation detecting system (4) has been used for multiaxial testing of wood tie and ballast. Subgrade soil and subballast have been tested in a 250 psi capacity multiaxial testing device (5).

The objective of this paper is to present descriptions of testing and constitutive models of