Application of Continuous Dynamic Compaction Control for Earthworks in Railroad Construction

ARIS A. SAMARAS, RÜDIGER LAMM, AND JOSEPH TREITERER

Continuous dynamic compaction control (CDCC) has been under development by the Federal German Railroad Authorities since 1985. The method can be used with vibrating compaction rollers of varying size and weight by measuring and recording the vertical acceleration pulses at the vibrating drum of the roller. The data are fed into a computer unit that combines the readings at the drum with other test data as the roller proceeds along the compaction area, and a continuous record of compaction data will be provided along the path of the compaction unit. Presented in this paper are the state of the art and first experiences in applying the CDCC method to the earthworks of a section of the new high-speed railroad track to be constructed between Mannheim and Stuttgart, West Germany. The following advantages are expected to be realized from the use of the new compaction control method: (a) previously used sampling methods could not provide full coverage of the construction area, and failures have occurred because of insufficient compaction data; (b) previously used spot measurements interrupted the flow of construction work extensively, thus limiting the number of samples that could be taken economically; and (c) CDCC provides a continuous compaction record, avoiding the repetition of unnecessary compaction passes and providing a more uniform compaction of the area at lower costs.

With the continuous improvement of ground transportation systems in Europe, the Federal German Railroad Authorities (FGRA) have been engaged in a program to upgrade mainlines for a speed of up to 250 km/hr (156 mph). Basic requirements of the program are extensive earthworks with uniform compaction of the subsoil and subgrade layers. It was found that the risk factor associated with random sampling was too high with fewer samples, and increasing the number of samples slowed the progress of the earthworks. New methods of continuous evaluation of compaction performance were therefore developed (*1–7*).

FGRA have developed standards for the degree of compaction and the resulting load bearing capacities in *Specifications for Earthworks* (*8*). The procedures and frequency of tests are given in the *Supplementary Technical Specifications and Guidelines for Earthworks in Highway Engineering* (*9,10*). The most frequently applied test methods are field density measurements to determine the degree of compaction and plate bearing tests to determine the deformation behavior.

A. A. Samaras, German Railroad Administration Karlsruhe, D-7500 Karlsruhe 1, Bahnhofstrasse 5, Germany. R. Lamm, Institute of Highway and Railroad Engineering, University of Karlsruhe, D-7500 Karlsruhe 1, Kaiserstrasse 12, Germany. J. Treiterer, 171 Medick Way, Worthington, Ohio 43085.

Continuous dynamic compaction control (CDCC) has not yet been included in the above regulations because the method is still in the development stage, and more data and research are required. Preliminary results, however, indicate that the method is reliable and successful in controlling and evaluating the compaction process with contractors.

REQUIREMENTS FOR THE CONTROL OF COMPACTION

Earthworks for FGRA must be carried out in agreement with the previously listed specifications (*8,9*). The quality of compaction is determined by four factors:

1. Degree of compaction (D_{Pr}),
2. Modulus of deformation, first loading (E_{v1}),
3. Modulus of deformation, second loading (E_{v2}), and
4. Ratio of E_{v2} to E_{v1}.

The moduli of deformation are determined by plate bearing tests in accordance with the German standard DIN 18 134 (*11*). E_{v1} is calculated by the first loading and unloading of the plate, which is intended to measure permanent settlement of the ground, which can be regarded as the plastic portion of the deflection. E_{v2} is determined by the second loading of the plate, which can be regarded as an elastic response. The modulus of subgrade reaction (k) is normally calculated for a mean plate deflection of 1,25 mm during the first and the subsequent unloading of the plate. Table 1 presents the minimum requirements for layers of the subgrade and the embankment.

In addition, it is required to determine the ratio E_{v2}/E_{v1}, which is introduced as an auxiliary criterion for the elastic behavior of the compacted ground. The limits of the ratio are given elsewhere (*9*), and the following requirements must be met for noncohesive soils: D_{Pr} greater than 103 percent, E_{v2}/E_{v1} less than 2.2; and D_{Pr} less than 103 percent, E_{v2}/E_{v1} less than 2.5.

The number of required tests by the conventional method (*9*) is presented in Table 2. The requirements for tests by the conventional method given in specification (*9*) are quite high, and it is hoped that CDCC will permit a reduction in the number of samples, resulting in considerable savings by simplifying compaction work for contractors. It is also hoped that considerable improvement of the standard tests results can be realized by combining the currently required sampling method with the CDCC method.

TABLE 1 MINIMUM REQUIREMENTS FOR SUBGRADE AND EMBANKMENT LAYERS (*8*)

SUBGRADE LAYERS	E_{v2} (MN/m^2)	D_{Pr} (%)
Top of 1. Layer	120	1.03
Top of 2. Layer	80	1.00
Top of Embankmant	60	0.97

Legend: E_{v2} = Modulus of Deformation (MN/m^2)

$D_{Pr} = \frac{\rho_d}{\rho_{Pr}}$ = Degree of Compaction (%)

ρ_d = Field Dry Density (t/m^3)

ρ_{Pr} = Maximum Dry Density (t/m^3)

CDCC METHOD

Measurement techniques for compaction control have been studied by FGRA since 1985 (*5*). The newly designed high-speed railroad section from Mannheim to Stuttgart has been selected for the first field application and test of CDCC, which

TABLE 2 MINIMUM REQUIRED DEGREE OF COMPACTION OR PLATE BEARING TESTS FOR THE INTERNAL QUALITY CONTROL OF THE CONTRACTOR (*9*)

TESTING ZONE	TEST POINTS		
	No. of Tests	Distance per Layer	Area per Layer
Subgrade	1	≤ 200 m	≤ 2500 m^2
Subsoil	1	≤ 200 m	≤ 5000 m^2

has been combined with the standard sampling method for the evaluation and verification of data. Vibrating rollers have been equipped accordingly, and Figure 1 shows the setup. The vertical acceleration pulses of the roller drum are registered by an acceleration recorder and processed by a computer for the display and permanent record of data. The time-dependent sequence of vertical accelerations generated by the vibrating drum (referred to as dynamic values) can be plotted by an *X-Y* recorder (Figure 2) and can also be presented by a computer plot, as shown in Figure 3. The output of the measuring system is installed in the cabin of the vibratory

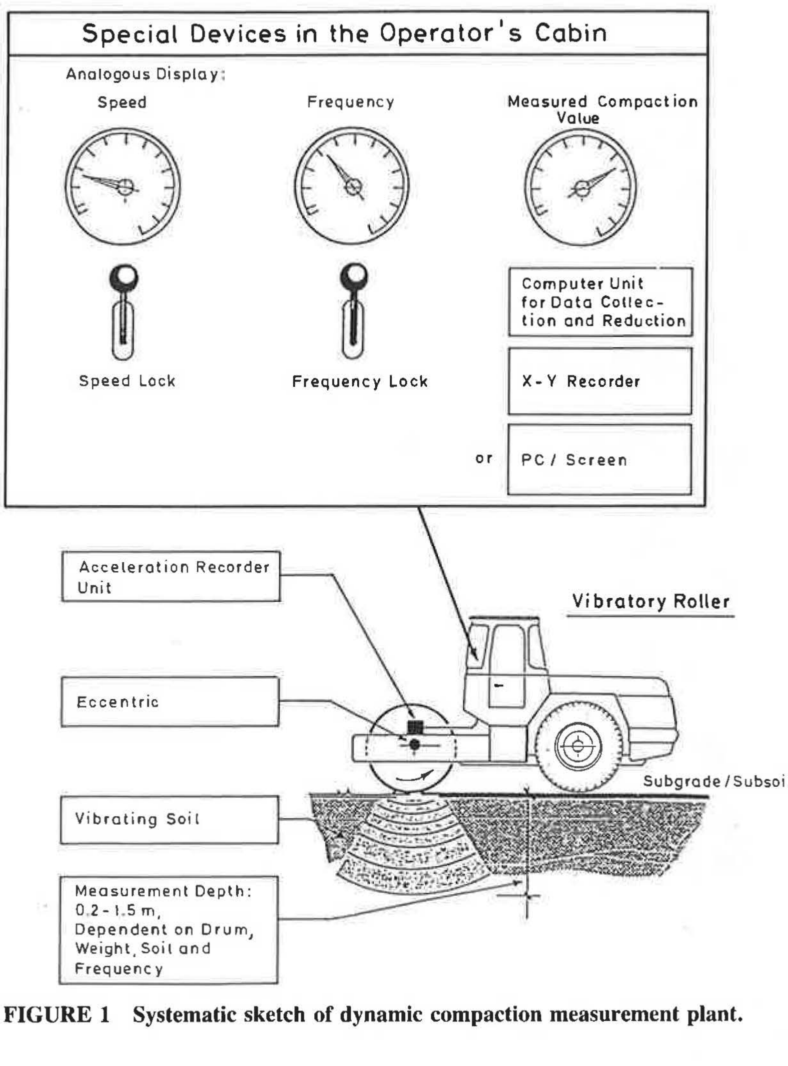

FIGURE 1 Systematic sketch of dynamic compaction measurement plant.

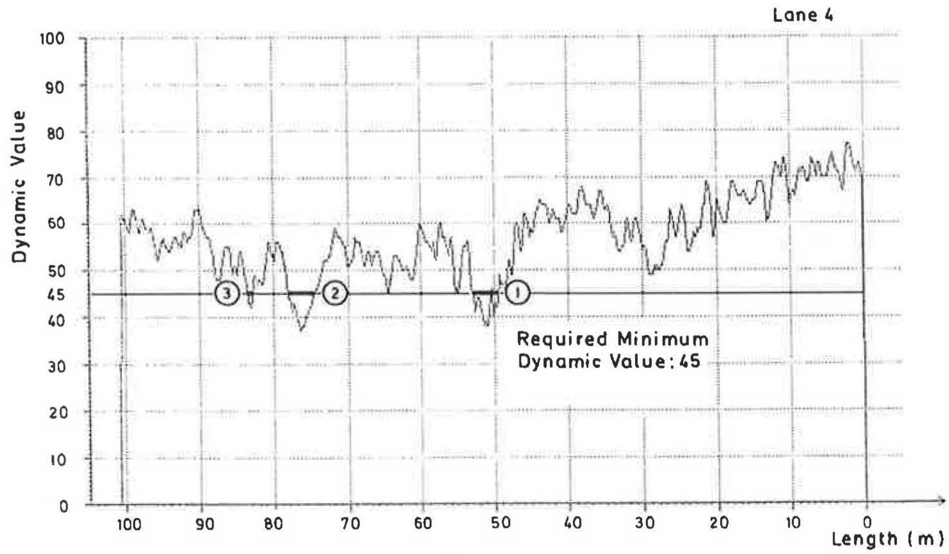

FIGURE 2 Example of lane-related *X-Y* recorded plot for dynamic value and length of the investigated section.

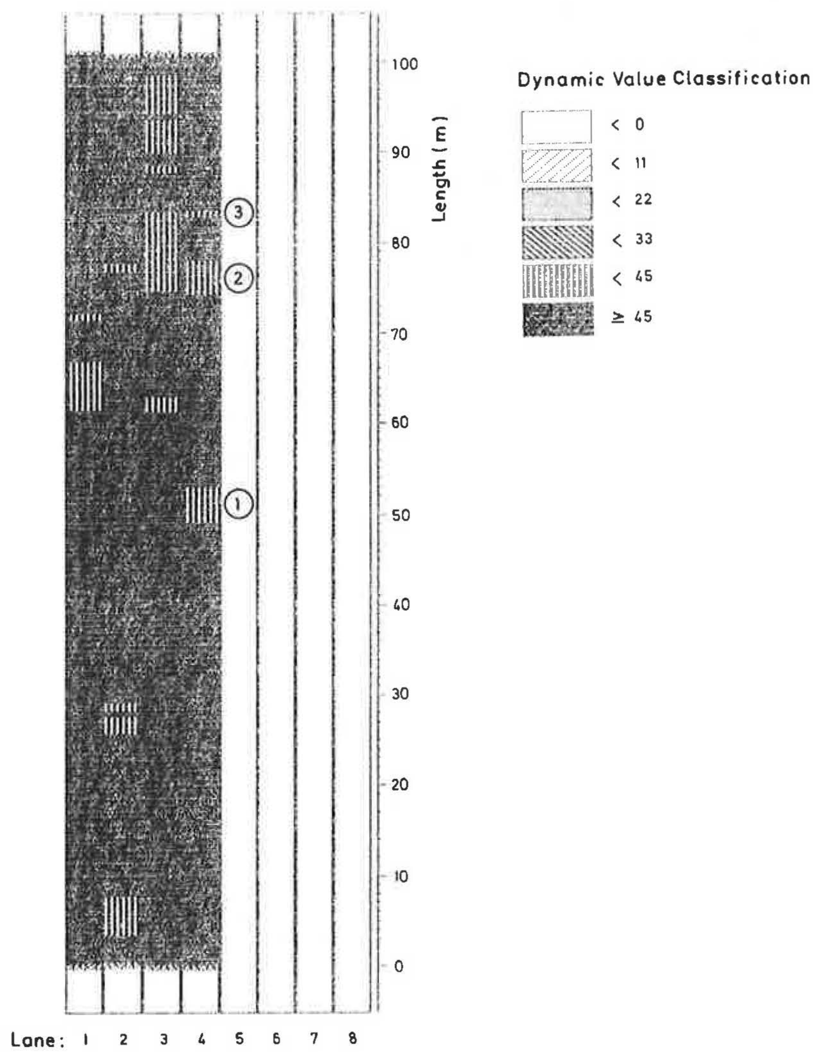

FIGURE 3 Example of computerized area plot for different dynamic value classes for length of the investigated section.

roller to aid the operator in meeting the required standard and to produce uniform compaction. No detailed description of the measuring ring system is currently available. The *X-Y* graph and the computerized area plot are used to supervise the compaction process and to provide evidence for the acceptance of compaction work carried out by the contractor. Figure 1 shows the display of operational settings, and Figures 2 and 3 reveal the measured and recorded compaction (dynamic) values, which enable the operator to adjust the passes to obtain the required uniform compaction of the area efficiently. Corresponding to the described principle, zones 1, 2, and 3 can be recognized as weak sections in meeting a required minimum dynamic value of 45, for example.

EVALUATION OF MEASUREMENTS AND INTERPRETATION

The measuring and recording system of the CDCC method presents a measured compaction value, a dynamic value considered to be a qualitative measure for the bearing capacity of the subsoil and subgrade. The dynamic measurements are influenced by the gradation of the soil, the density, and, with an increasing portion of the fines, by the moisture content of the soil. Contrary to the determination of the density, the dynamic CDCC value is not related to a constant volume but presents a qualitative value of the dynamically excited ground under the drum of the vibratory roller. The depth of influence is variable and depends on the weight and width of the drum, the power of the dynamic excitation, and the properties of the soil. Depending on the soil properties and the type of vibrating roller, the test was found to reach to a maximum depth of about 1.5 meters, covering a thickness of layers that is beyond the range of conventional soil-testing methods. The relationship between the CDCC test and the results of penetration and density tests is doubtful because of the difference in volume covered by the tests. The plate test, with an influence depth of 1.5 times the plate diameter, appears to be more suitable for comparison.

The comparative evaluation of dynamic measurements and supplementary field and laboratory tests lead to characteristic ranges of validity. Figure 4 shows these ranges for noncohesive soils, which have been determined from numerous individual tests of modulus of deformation and density and the dynamic values at corresponding test locations. It appears that the plate bearing test and the corresponding modulus of deformation, E_{v2}, is of special interest in comparison with the dynamic value. The regression curve in Figure 4 represents, as an example, the relationship between the E_{v2} values and the dynamic values for a granular soil used for frost protection.

The modulus of deformation should exceed 80 MN/m^2 according to the specified requirements in Table 1. The regression curve of Figure 4 shows a dynamic value of 32 MN/m^2. However, it was found from previous experience that the reading from the regression curve should be increased by a safety margin of 10 percent because the available data from samples have not yet been established statistically. It was found, however, that the density tests and the requirements for the ratio E_{v2}/E_{v1} are met if the regression curve is covered by the range of valid E_{v2} values.

To obtain reliable results with the CDCC method the following conditions must be met:

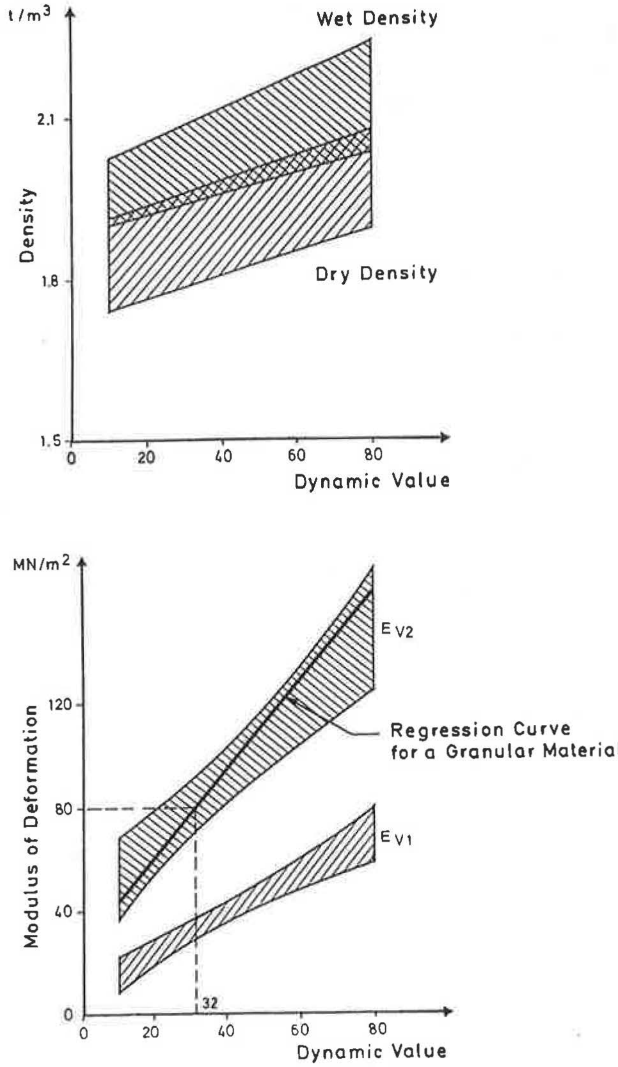

FIGURE 4 Ranges of validity between dynamic value and modulus of deformation and density for investigated noncohesive soils.

- The drum of the vibrating roller must have good, continuous contact with the ground, and the variation of a flat surface should not exceed 5 cm within a range of 4 m.
- Soft surfaces should be avoided because they can cause slippage of the drum and unreliable data.
- Hard surfaces should be avoided because they can cause bouncing of the drum, which will result in bad measurements.
- The rotational direction of the eccentric will be changed during reverse operation of the roller, resulting in less efficient compaction. Test passes should therefore be conducted in the forward motion only.
- The energy input to the dynamically excited soil is influenced by the speed of the roller and the frequency of the vibration. Both factors must therefore be kept constant for test passages.

CONCLUSION

The CDCC method offers substantial improvement in uniform soil compaction and in the control and record keeping for contracts with earthwork. This paper is based on the methods and experience of a single construction project carried out by the FGRA covering noncohesive soils only. More data and research are needed to develop CDCC to its full advantage for field applications, and it is hoped that this paper will provide some incentive for further exploration and research.

ACKNOWLEDGMENT

The authors wish to thank A. Dengiz for his assistance in preparing and translating this paper.

REFERENCES

1. R. Floss, N. Gruber, and J. Obermayer. A Dynamical Test Method for Continuous Compaction Control. *Proc., Improvement of Ground*, Vol. 1, Helsinki, Finland, 1983, pp. 25–30.
2. R. Floss. Dynamic Compaction Control in Earthworks. *International Technical Journal: Road and Autobahn*, Vol. 2, 1985, pp. 52–57.
3. R. Floss and W. Kroeber. *Continuous Dynamic Compaction Method for Quality Control in Earthworks. Conference on Foundation Engineering*, German Foundation Engineering Association, Federal Republic of Germany, 1988, pp. 193–204.
4. N. Gruber, J. Obermayer, and R. Floss. Acceleration Measurements of Vibratory Rollers as Control for Compaction. *Symposium for Measuring Techniques in Earthworks and Foundation Engineering*, Munich, Federal Republic of Germany, 1983, pp. 71–77.
5. A. Samaras, and G. Spata. New Railroad Section Mannheim-Stuttgart: Improvement of Quality in Earthworks with the Continuous Dynamic Compaction Control—Tests and Applications. *Journal: The Federal Railways*, Vol. 5, 1987, pp. 465–471.
6. R. Kirschner. Dynamic Control of Compaction in Earthworks. *International Technical Journal: Road and Construction*, Vol. 6, 1986, pp. 18–23.
7. W. Kroeber. *Dynamic Analysis of Vibratory Compaction in Earthworks*. Publications of the Institute for Foundation Engineering, Soil and Rock Mechanics, Technical University of Munich, Vol. 11, Federal Republic of Germany, 1988.
8. *Specifications for Earthworks* (1985 ed.). DS 836. German Federal Railways, 1985.
9. Supplementary Technical Specifications and Guidelines for Earthworks in Highway Engineering (1978 ed.). ZTVE-StB 76/78. Minister of Transportation, Division of Road Construction, Federal Republic of Germany, 1978.
10. R. Floss. *Comments to the Supplementary Technical Specifications and Guidelines for Earthworks in Highway Engineering*. ZTVE-StB 76/78. Kirschbaum Publishers, Bonn-Bad Godesberg, Federal Republic of Germany, 1979.
11. *DIN 18 134—The Plate Bearing Test*. Werner Publishers Inc., Düsseldorf, P.O. Box 8529, Federal Republic of Germany.

This paper is not a final report on CDCC. It is intended to present a description of the method, which is still in development, and a summary of the experience obtained thus far from an FGRA construction project.

Publication of this paper sponsored by Committee on Transportation Earthworks.