Intelligent Systems for QA/QC in soil compaction

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Abstract: Continuous Compaction Control (CCC) is a well-established method for the online, quality assessment and quality control of 100 percent of an area of soil being compacted by vibrating or oscillating rollers. The method is based on the use of a roller-integrated compaction meter that treats the roller drum as a dynamic loading object. The vibration of the roller drum is measured with an accelerometer, the output signal of which is analyzed using a microprocessor. The result is then presented to the roller operator as a numerical value and/or a graphical symbol indicating the achieved soil stiffness. The numerical values are stored for later retrieval using a PC. This makes it possible to generate various charts and reports for quality control documentation. The paper briefly describes the development and theoretical foundations of available compaction meters as well as their applications in CCC. The importance of CCC for improving the quality of the underlying surface of asphalt pavement, and thus the overall quality of a road project, is emphasized. The need for solid federal/state standards is called for, and the standards for CCC implemented by the Swedish Road Administration are briefly discussed. The paper contains 19 references, many of which describe extensive practical use as well as the results obtained.

INTRODUCTION

Maintenance costs are steadily contributing to increased life-cycle costs for road construction. Even though soil compaction costs constitute only a small fraction of the total costs, quality in terms of area-covering roadbase homogeneity is of paramount importance if acceptable quality is to be achieved in surfaced-road construction.

One way of introducing a 100-percent area-covering method for quality control is by employing Continuous Compaction Control (CCC), which is based on a roller-integrated compaction meter. Such a meter was first presented at a conference on compaction in Paris in 1980. The instrument was called the “Compactometer” and several papers, for example [2] and [12], dealt with R&D-results as well as with experience from the field.

The Compactometer was the first step taken in the transition from traditional soil compaction to modern CCC. Easy-to-use modern electronics, based on microprocessors and digital-signal processing, assist a roller operator in carrying out process control. The aim is to achieve efficient compaction work and a homogeneous compaction result. The use of CCC has made it possible to replace previously detailed specifications with function contracts (BOTs), giving a contractor an excellent and necessary tool for QA/QC regarding the compaction process.

In order to achieve still higher compaction productivity and even better homogenous compaction results, the rollers must themselves be made more ‘intelligent’. This can be done by designing them to automatically adapt to varying stages of compaction and soil conditions.

TRADITIONAL SOIL COMPACTION

Traditionally, soil and rock fill materials are compacted with static or vibrating rollers. In the last 20 years or so, this has also been done using oscillating rollers [6], [10]. Compaction of a certain area is carried out by employing parallel strips—either edge to edge or with some overlap—each strip being covered using a fixed number of passes. Most rollers are rotating eccentric-vibrating rollers. Their vibration frequency and amplitude is kept constant while the roller operator controls the roller’s speed.

It is obvious, however, that the use of a specific number of passes and constant roller speed, as well as vibration frequency and amplitude, will not achieve homogeneous compaction in the case of layers that consist of varying material properties and varying water content, particularly where the underlying layers have heterogeneous stiffness. Instead, the employment of such parameters will always leave a certain area insufficiently compacted and another area overcompacted, with only the remaining area sufficiently compacted.

Traditionally, the level of compaction from using a heavy vibrating roller is checked by some spot-test method such as water balloon or nuclear density test. These methods normally have a sample volume of about two liters, which can never represent the compaction results for the entire area reliably, nor contribute to an improvement in compaction-work homogeneity.

Most spot-test methods are also time consuming—with hours or days passing until the results can be presented. Such tests will, in addition, bring about delays or a stop in construction work, because they have to be carried out without any disturbing vibrations in the vicinity of the test spot.

Neither proof rolling nor efforts to compact until no further deformation behind the compacting drum is achieved will ever be able to meet modern requirements for homogeneous compaction results.

INTELLIGENT SOIL COMPACTION

Compaction Meters

Compactometer

The drum of a vibrating roller subjects the soil to repeated blows—normally one per vibration cycle. As in the case of a dynamic plate-load test, the blows from the cylindrical drum can be used as a load test of the soil.

This idea was evaluated in numerous field tests that employed test rollers as well as production rollers equipped with accelerometers [3], [8], [12]. It was found that the ratio between the amplitude of the first harmonic and the amplitude of the fundamental frequency was significant for the compaction level achieved.

It can also be shown that the force amplitude ‘F’ of the blows is proportional to the first harmonic of the vertical acceleration of the drum. The displacement ‘s’ during the blow can be approximated by the amplitude of the double integral of the fundamental acceleration component [9]. Therefore, it is relevant to express a “cylinder deformation module” E_c as the ratio of the force and the corresponding displacement as

$$E_c = c_1 * F / s = c_2 * A_1 / (A_0 / \omega^2)$$

where

ω	= fundamental angular frequency of the vibration
A_0	= acceleration amplitude of the fundamental component of the vibration
A_1	= acceleration amplitude of the first harmonic component of the vibration
c_1 , c_2	= constants

This is the basis for defining the Compaction Meter Value as

$$CMV = 300 * A_1 / A_0$$

where the constant has been chosen to give a full scale reading of 100.

The measured CMV will vary from roller to roller, and the roller parameters—especially the frequency—have to be kept constant and equal to the parameters used during a calibration. A roller operated at a standardized setting, however, could be used equally well as a Falling Weight Deflectometer for the assessment of surface stiffness. The great advantages of using a ‘standardized’ roller as a measuring tool are that a complete coverage of the area is obtained and that the result can be displayed instantaneously**.**

The instantaneous CMV is normally shown on a dial located in the roller cabin. Observation of the CMV-dial will indicate to a roller operator what CMV he is achieving right under the roller drum. Comparing this CMV with a recommended or calibrated CMV-minimum, the operator is able to see where sufficient compaction levels have been reached and where additional passes are needed.

Oscillometer

A compaction meter for use with oscillatory rollers has been developed [10]. It is based on a measurement of the horizontal acceleration of the center axis of the drum. When the drum is operated at frequencies above the resonance, and there is no slip, the amplitude of this signal is a function of soil stiffness as well as the roller parameters. This stiffness value, called OMV, is quite insensitive to moderate variations in the excitation frequency.

When there is slip between drum and soil, the signal processor of the oscillometer uses a special algorithm to calculate the OMV. This calculation is based solely on the time intervals during which the soil and the drum move together without slipping.

Compaction meters based on other concepts

As a byproduct of the development of Intelligent Compaction Machines (ICMs), Geodynamik developed a mathematical model to calculate a stiffness module G and a plastic parameter p based on the recorded acceleration of the roller drum and the instantaneous position of the eccenter weights [11]. The result, primarily used for controlling a roller, could also be presented as a stiffness value for the soil. The shear modulus G can easily be recalculated to an E-modulus for convenient comparison with standard spot-test results.

In recent years, there has been some development along similar lines both in Switzerland and in Germany [1], [5], and compaction meters based on these concepts have been introduced on the market.

Common to all these methods is that the contact force between drum and soil is calculated from the recorded drum acceleration and the eccenter phase. The movement of the drum in a vertical direction is calculated by integrating the acceleration twice.

Other compaction meters on the market are based on a model where the contact zone is treated as an elastic contact between a flat, elastic half-space and a horizontal cylinder having infinite stiffness [7]. The load/displacement relationship for this contact zone is nearly linear, and the zone cannot therefore exhibit any irreversible deformation. A load/displacement cycle, Figure 1, will be an ellipse, or a truncated ellipse if the drum lifts off

For most soils, however, a failure zone—eventually leading to plastic deformation—develops as the cylindrical drum surface loads the soil surface. The contact area is initially zero when the cylinder first makes contact and expands as the drum moves downwards and contact force increases.

A typical load/displacement cycle—when the drum lifts off from the ground and a fairly large amount of plastic deformation takes place—is shown in Figure 2. The inclination of the loading part (A-B) cannot be used directly as a measure of the E-modulus of the soil, because the total displacement consists of contributions from both plastic and elastic effects.

Further development

As has been mentioned above, a constant number of passes and constant roller parameters will always leave a certain part of the area insufficiently compacted and another part overcompacted, with only the remaining area sufficiently compacted. Soil conditions generally vary a great deal. It is therefore evident that there is much to gain from using a roller that automatically adapts to varying conditions. Not only will it adapt automatically to varying soil conditions, such a roller will also achieve the highest possible efficiency from the first to the last pass over the entire area.

The first prototype of a GEODYNAMIK “Intelligent Compaction Machine, ICM” was on display already in 1992. In the years since then, development has continued but a product is not yet available on the market.

CONTINUOUS COMPACTION CONTROL — CCC

Continuous Compaction Control (CCC) is a method for online, quality assessment of 100 percent of the area being compacted. The method is based on the use of a roller-integrated compaction meter such as the Compactometer, the Oscillometer, or other comparable compaction meters [13], [14], [15], [16]. The compaction meter value is stored in and displayed by a unit in the roller cabin. On this display, a roller operator can observe the position of the roller relative to the compaction area. There are also indicators for roller speed and vibration frequency. In addition to the graphic image, compaction results are also presented as digital values for individual passes and strips.

CCC roller equipment

A CCC-system typically consists of four components, Figure 3. An accelerometer is located close to the roller-drum axis in order to measure the vertical component of drum acceleration. This analog signal is measured, transformed into digital form, and then processed by a digital-signal processor located either in or in close proximity to the roller cabin. The compaction meter values thus obtained are stored and presented in the roller cabin on a graphical display that represents the area being compacted. In order to obtain information on where the roller is situated along a strip, an inductive speed sensor is mounted on the rear axis. This sensor is connected to the display unit in the roller cabin, thereby continuously updating the roller’s position.

The GEODYNAMIK COMPACTION INDICATOR, CI, Figure 4, uses an LED-matrix and a mini-display. The LED-matrix indicates (in a simple and easy readable way in green color) where compaction results have been reached or exceeded and (in red color) where additional passes are needed. On the mini-display, the roller operator can read the CMV from directly under the roller drum. The roller speed, the vibration frequency, and the distance traveled from the starting line are also displayed.

A more advanced tool for CCC, which allows the transfer of compaction data to a PC for charting and reporting, is the GEODYNAMIK COMPACTION DOCUMENTATION SYSTEM (CDS), Figure 5. A roller operator can watch indicators for travel speed and vibration frequency on a 'working screen', and also follow the position of the roller by means of a roller symbol.

Interpretation of CCC-readouts

It is important to keep in mind that the CCC-method uses the roller as a measuring tool, quantifying the soil conditions via the roller's dynamic response. This means that results are related mainly to the stiffness of the layer as seen from the surface. The damping conditions from plastic deformations and viscous effects are also included to some extent. Consequently, results from CCC measurements cannot, and should not, be expected to correspond directly to the density or to the degree of layer compaction. This is particularly true in the case of fine-grained materials with optimum or above-optimum water content, when the relationship between density and stiffness is rather weak or even nonexistent.

Another important factor when interpreting CCC-results are the two different depth ranges involved. The depth range of the compaction effect is governed by the level of stress and acceleration that is generated by the roller. These levels must exceed certain threshold values in order to bring about a rearrangement of the grains. The compaction depth is therefore dependent on the size of the roller, the level of force it can generate, and the frequency of vibration.

The depth range of the CCC-measurement method is not limited, however, by a stress or acceleration threshold and can therefore extend to relatively great depths. The CMV is an integral with contribution from large depths with the highest weighting of the layers closest to the surface. Generally, the CMV represents soil conditions to a greater depth than the compaction depth.

Optional charting and reporting

Using a GEODYNAMIK COMPACTION DOCUMENTATION SYSTEM (CDS) in a roller makes it possible for an operator to maintain far better control of his work than watching a dial that is constantly changing. In addition, the storage of the compaction results in the CDS allows for the transfer of data to a PC, which in turn allows for the processing of large amounts of compaction data from a big project in a convenient way. One is able, for instance, to make printed reports ready for filing or study selected areas in detail to unveil possible faults in soil structure.

QA/QC OF SOIL COMPACTION IN ROAD CONSTRUCTION

Maintenance and repair costs are increasingly influencing the life-cycle costs of road constructions, which consequently contributes to a slowing down of economic growth. Higher quality, i.e. homogeneity and stability of a road, can be reached by the introduction of Continuous Compaction Control (CCC), particularly in the QA/QC process of soil compaction. Even though the cost for soil compaction is only a small fraction of the total construction cost for a modern high-speed highway, it is very well known that an insufficiently and inhomogeneously compacted pavement layer may rapidly lead to serious damage to the surface of the asphalt—thus necessitating premature rework.

It is important to keep in mind that an introduction of CCC as standard tool for the QA/QC process needs to involve a whole chain of actors extending from the federal authorities down to the roller operator.

Standards

The successful introduction of CCC for QA/QC purposes has been made in several countries, particularly Germany, Austria, and Sweden[17],[18], [19]. Common to them all is the establishment of rigid federal/government standards that must take into account geotechnical considerations. These standards must also be designed in such a way that they are easily adopted and accepted by buyers and contractors.

In Sweden, the CCC-standard is presently designed in such a way that a buyer can choose to require a contractor to perform CCC according to this standard, instead of using traditional plate-load testing and statistical evaluation. The buyer can also leave this decision up to the contractor as long as the stiffness criteria set forth by the standard are fulfilled. If, however, CCC is chosen, it is possible to reduce the number of spot tests that are needed to accept or reject the tested area from eight points per 5000 m^2 to only two. In addition to this, stiffness criteria can be lowered by 20 percent when using CCC, because uncertainty in the QA process is greatly reduced owing to the 100-percent area coverage. Nonetheless, spot tests cannot be completely avoided as of yet, since CCC is only a relative measurement method in need of calibration.

The Swedish road authority has shown by calculations [4] that the cost for performing QA using CCC for a 10-km-long highway can be reduced by up to 40 percent.

Buyers

A breakthrough for BOT contracts in road construction projects has long been awaited in Europe. Although these have been tried out in a number of countries, there has been unexpectedly slow acceptance. If BOT contracts are to become widely accepted, it is imperative that reliable QA/QC methods be made available. For soil compaction in the construction of roads, CCC is such a method.

There is, however, no need to simply sit and wait in order to introduce CCC. Buyers should already be requiring contractors to apply CCC in the QA/QC process. The main advantages are:

- 100 percent of the compacted area is subjected to QA thus minimizing inhomogeneities and premature rework
- With the help of a CDS system, the results of the compaction process can be documented on computer media. This is very useful when searching for causes in the case of later, unexpected damage.

Contractors

The average lifetime of a road is about 12 years. At the same time, a contractor's warranty period in Europe is 4 to 5 years. It is apparent that this warranty period will be extended in a not-too-distant future. If a contractor wants to offer a longer life time for his construction work, he will have to implement a reliable quality assurance system from the very start of the construction work—a system that covers each square meter and assists the machine operators in optimizing their work, thus avoiding unnecessary compaction passes. In addition, a system for continuous quality assurance will provide both contractor and customer with instant job documentation on site.

Roller operators

CCC must not be seen merely as a means of documenting compaction results. An important purpose of CCC is to guide the performance of the compaction process in order to achieve homogeneous compaction results in a minimum of time. Homogeneity means a minimum of undercompacted and overcompacted spots and, consequently, a minimum of maintenance and repair costs.

The information shown on the screen can be used during compaction to guide the work. An operator can avoid unnecessary overcompaction and concentrate work on parts that need more passes. Using the screen information, he will also be able to locate incompactable weak spots and initiate supplementary measures, for example, the use of a different roller and either stabilizing the material or replacing it.

CONCLUSIONS

Continuous Compaction Control (CCC) is a well-proven method originally devised by GEODYNAMIK for QA/QC of soil compaction in road construction. The innovative design is a direct result of numerous field tests, which have been extensively reported in geotechnical literature [1], [6], [8]. Used together with well-known and documented signal processing methods, CCC is able to provide for Quality Assurance by presenting an operator with instantaneous information about the level of compaction achieved directly online. Furthermore, full surface-covering Quality Control documentation for optional charting and reporting can be provided through a documentation system.

The cost for soil compaction is only a small part of the total construction cost. Improved quality in terms of compaction homogeneity for the work being done, however, plays a far more important role for the life-cycle costs of a project, because this minimizes the amount and frequency of asphalt-paving rework needed.

The CCC-method, along with solid federal/state standards aimed at saving costs for a contractor, is a prerequisite for the soil compaction process. This is particularly true if federal/state buyers and contractors are to continue to push for the implementation of BOT-contracts for road construction.

The next step in increasing the efficiency of the soil compaction process is to equip rollers with a suitable amount of 'intelligence', thus making them adapt automatically to varying soil conditions during the compaction process. Using the prototype displayed more than 10 years ago, GEODYNAMIK continues this development for new roller concepts being introduced on the market.

LIST OF FIGURES

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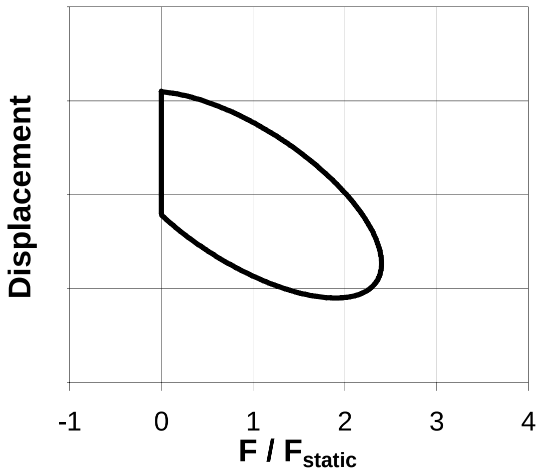


FIGURE 1 Calculated load/displacement cycle for soil with linear drum/soil interface

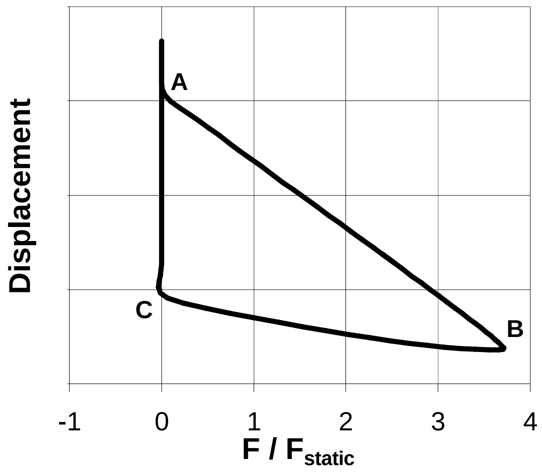


FIGURE 2 Calculated load/displacement cycle for soil with elastic and plastic deformation

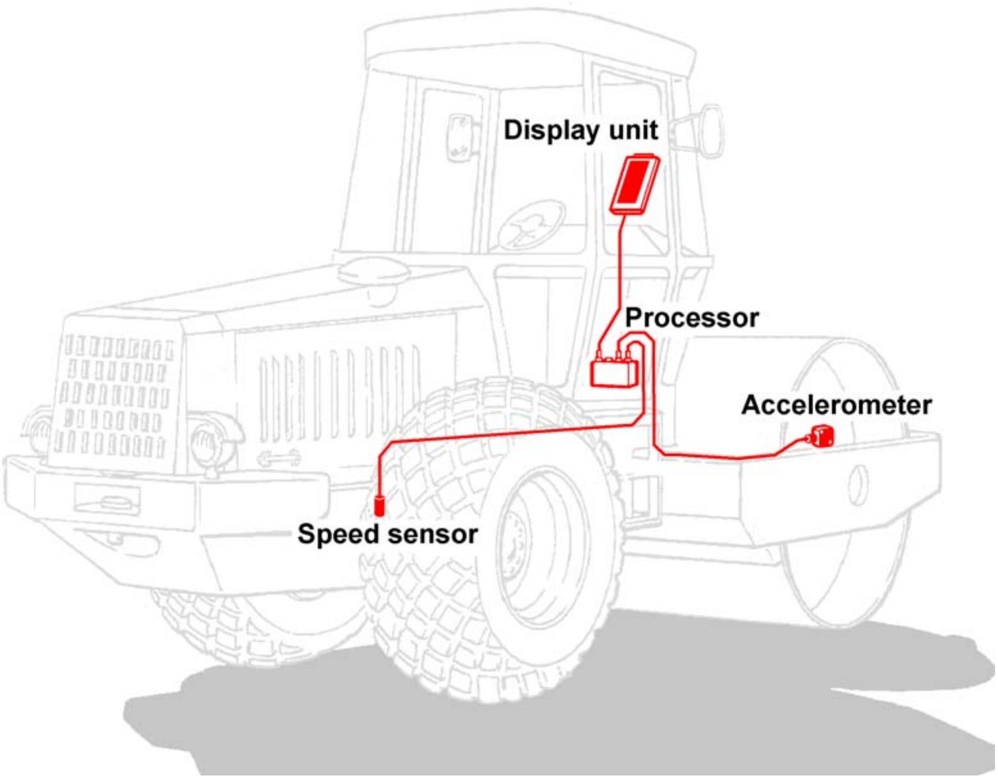


FIGURE 3 GEODYNAMIK Compaction Documentation System

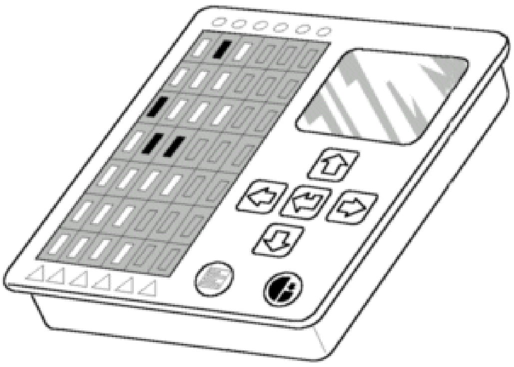


FIGURE 4 GEODYNAMIK Compaction Indicator display

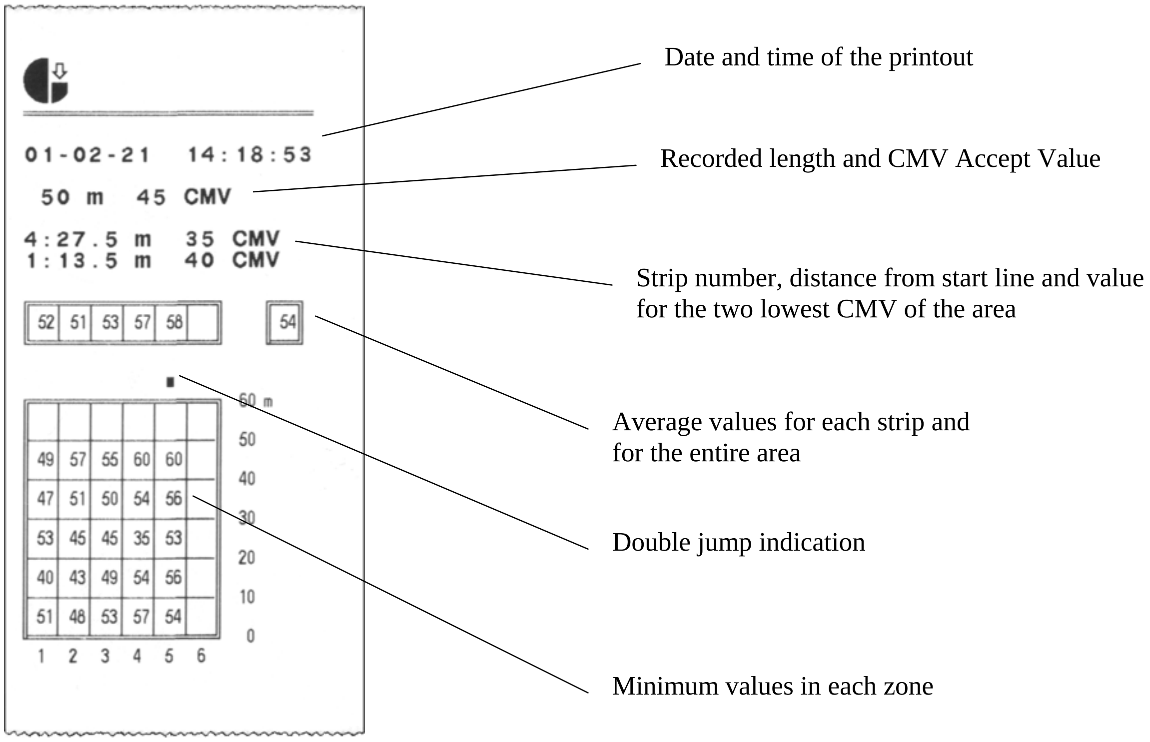


FIGURE 5 Printed output from Compaction Indicator system

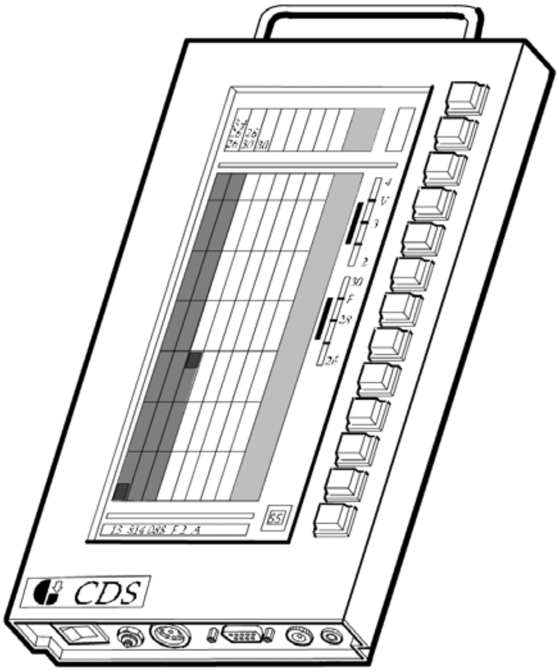
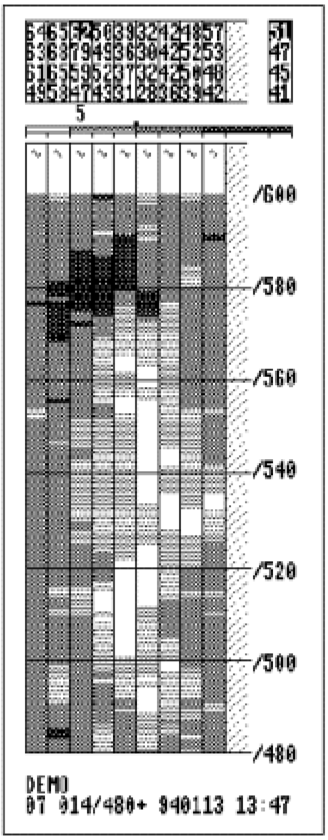


FIGURE 6 GEODYNAMIK Compaction Documentation System display



CDS-012J
Compaction Documentation System

GEODYNAMIK AB
97-04-15 15:56

PROJECT : DEMO

ROLLER DATA
Model : TEST
Weight : 8000 kg
Width : 210/200 cm
Amplitude : 0.8/1.6 mm

CALIBRATION VALUES
Layer : 2 A SUB-BASE
f: 28 Hz v: 3.0 km/h A: low

STRIP MARKINGS for
f-deviation > 2% (27.4-28.6)
Double jump > 10%
v-deviation > 10% (2.7- 3.3)

RESULTS - LAST PASS
Max striplength : 120.0 m
Compacted area : 2159 m²
One value : 2.2 m²

COMPACTION METER VALUES

Number	Mean	SD	CV
990	51.1	19.9	39%

< 50: 888 m² (41%)

Limit	20	50	80
Area	192	888	2024 m²
	9	41	94 %

FREQUENCY/SPEED

	Min	Mean	Max
f	27.1	28.0	28.5 Hz
v	2.7	3.0	3.2 km/h

REF DIST: 12.3 m right

JUDGEMENT:

FIGURE 7 Sample output from Compaction Documentation System: CCC-protocol