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CENTER FOR TRANSPORTATION STUDIES

RESEARCH REPORT

RAPID DETERMINATION OF FIELD PROPERTIES OF COMPACTED MATERIALS

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16. Abstract (Limit: 200 words)

The report describes the results of a limited investigation into the technical progress and acceptance of techniques for field determination of the engineering properties of compacted materials. Although some of these techniques have been investigated for several decades, few are in common use. The reports discusses the benefits and limitations of the principal techniques and concentrates on acceptance issues for their use in practice.

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Rapid Determination of Field Properties of Compacted Materials

FINAL REPORT

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Executive Summary

The purpose of this review was to try and understand why rapid seismic/impact methods of soil property determination suitable for compaction control have been around in principle for several decades and yet have not won widespread adoption. Further, it was to speculate if continuing changes in the technologies would result in the methods becoming more widely used and in turn improve the quality and cost-effectivenss of compacted fills.

There would be a number of benefits to the compaction process from successful, easily-implemented, and cost-effective techniques for the rapid determination of the the properties of compacted materials. These include:

- Compaction energy can be concentrated on surfaces that need it most
- Better homogeneity in the compacted material
- Lower cost and risk for the contractor and owner
- Properties such as strength, stiffness can be determined though correlations
- More rapid feedback on acceptability of the work so that defective work can be corrected before it is covered up
- Assesses more directly properties of interest in the stress/strain response of soils such as elastic modulus
- Assesses more directly the effect of moisture changes on the structure of the soil as well as maximum compacted dry density (i.e. wet of optimum vs. dry of optimum compaction)

The principal advantages of the use of seismic/impact techniques to measure near-surface soil properties are:

- with progressive improvements in signal processing and analysis, results are now available almost instantaneously (as compared to results from sand cone tests which are not available for a day)
- the equipment can be highly portable and does not need a radiation source (as compared to nuclear density tests)
- the tests can often be adjusted to measure the average properties of different depths of soil
- the tests may allow a direct measurement of the dynamic modulus of the soil which is important in pavement response to traffic loadings

The conclusion of this review is that the methods continue to show promise and progress in adoption. On the other hand, it has not been surprising that they have not won widespread use as yet. There have been major technical difficulties in terms of variable or difficult to interpret results that depend on local site conditions, there is the potential loss of connection to the large database of experience and correlations available for traditional methods of assessment, there has been a specialist knowledge required that may not be present in the companies that do the current testing, and the field equipment has often not been rugged enough or powerful enough to provide real-time on-site results.

It appears that these problems are slowly being resolved and that adoption of the techniques is gradually occuring -- faster in Europe than in the U.S.

Faster and more widespread adoption will most likely come from the desires of owners for better compaction control or from contractors for better cost control in meeting compaction specifications. The use of the systems will likely accelerate once they are in moderate use because of greater familiarity with the benefits of using the systems, the reduction in liability that occurs with increasing use, and the increasing confidence that would develop in interpreting the results of the measurements and relating them to the accumulated experience in the performance of compacted fills.

The ability of the methods to measure dynamic soil moduli directly is a benefit for transient loading conditions such as in road pavement design but much more will need to be done to tie the results of these measurements to the actual performance of roadway pavements before the benefits of this additional knowledge will be realized. The increasing use of mechanistic analyses of pavements in design and pavement evaluation (the falling weight deflectometer, for example) will accelerate this adoption.

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Chapter 1
Introduction

1.1 Background to the Study

In 1994, a local engineering firm, Charles R. Nelson & Associates, Inc. and a national acoustics/computer sciences firm, Bolt, Beranek and Newman, Inc. collaborated on some field trials on the use of wide band seismic techniques for determining the engineering properties of soil layers compacted as part of road construction. The experimental and analytical techniques used in this type of study have become progressively more user friendly, more portable, and less expensive over the past few years. There have been adjustments to the scope of the testing in terms of the use of frequency response spectrums rather than results of single impacts or single forcing frequencies. These adjustments also have improved the repeatability and quality of the results.

In discussions with the Minnesota Department of Transportation (MnDOT) which followed the testing, several issues were raised concerning the future potential of these techniques. The results presented looked very promising but since similar approaches were first proposed and tested several decades ago, the obvious question asked was why these techniques haven't been more widely adopted and whether the current developments underway are sufficient to overcome the impediments which have apparently been present up to this time. The discussion also highlighted the lack of information which might allow an understanding of how the properties of a compacted soil change after its placement - due, for example, to changes in moisture content, changes in stress or the effect of freeze-thaw cycles. Other issues raised were questions about whether test strips would be needed to calibrate the measurements for particular soils and the possibility that the method could also be used to measure in-place properties of asphalt materials.

A small project was initiated to study the above issues to aid in the review of the applicability of rapid techniques for soil property testing. This project was started in 1994 but completion of the report was delayed by the closure of the Underground Space Center at the University of Minnesota and the subsequent relocation of the Principal Investigator for this project to Louisiana Tech University.

1.2 Scope of Study

In order to seek answers to the questions posed above, a literature search was conducted on the general topic of the determination of field properties of compacted soil and aggregate materials and the technologies suitable for this purpose. A number of researchers and equipment manufacturers were also contacted to discuss issues regarding the adoption of these technologies.

This report provides an overview of the study and gives:

1. An outline of the techniques used in determining shallow soil properties especially for compaction measurement and control purposes.
2. The interpreted reasons why the newer techniques for rapid determination of soil properties using seismic or impact techniques currently are not used more widely and whether the advances in equipment and/or technique have overcome the drawbacks for use today or in the near future.

Due to the closure of the Underground Space Center and ensuing faculty, staff and student dislocations, the staffing and timing of the study were significantly affected. Loss of graduate student availability and principal investigator activities connected with the closure of the center curtailed the planned depth of review.

1.3 Techniques Considered

There are a variety of traditional and newer methods of assessing the suitability of in-situ or compacted soils for engineering purposes. Many of the newer techniques make use of geophysical methods of investigation and the range of methods available and the parameter being measured is listed in Table 1.

Table 1 Commonly Used Surface Geophysical Methods

METHOD	MEASURED PARAMETER
Ground Penetrating Radar	Two way travel time (complex dielectric constant)
Electromagnetic	Electrical conductivity
Very Low Frequency Electromagnetics (VLF)	Electrical conductivity
Resistivity	Electrical resistivity
Streaming Potential (SP)	Electrochemical and streaming potential
Seismic Refraction	Travel time (seismic velocity)
Seismic Reflection	Two-way travel time (density and velocity)
Magnetics	Magnetic susceptibility/permeability
Metal detector	Electric conductivity of metal
Gravity	Density
Thermal	Temperature
Radiometric	Radiation (gamma rays)

(Source Benson and Yuhr, 1996)

The different geophysical techniques have different strengths and weaknesses in determining information about below-ground soil conditions. There are trade-offs between resolution of methods and the depth of soil that can be penetrated (typically, high frequencies give better resolution but less depth penetration) and some methods are less suitable in certain environments (e.g. electromagnetics may be subject to interference in urban areas) or certain soil types (e.g. the effective depth of ground penetrating radar may be less than one meter in saturated clays). Many methods can be used to find information about the zonation of subsurface materials and buried objects. Fewer methods give useful information about the mechanical properties of subsurface materials that relate to the performance of these materials in structural applications such as road bases.

The techniques most applicable to compaction determination are seismic methods that involve the transmission of a shear or compression wave through the soil, microgravity methods that compare densities of soil zones, and nuclear methods that measure local soil densities or moisture contents.

The equipment for making microgravity determinations is only just reaching a point where such techniques can be used reliably for finding near-surface soil voids. They do not yet appear to be at the point where they could be used for local soil density comparisons. Nuclear density meters are reasonably well accepted in the compaction control process and will not be considered in detail in this report. The principal range of techniques considered in this report will be those based on the generation of seismic waves in the soil or those based on the effect of impact loads on the soil. These techniques face some common issues in gaining acceptance as useful techniques for measuring or controlling the mechanical properties of soils.

Chapter 2
Review of Available Methods

2.1 Technologies used to Measure, Infer or Control Soil Properties

A brief outline of the technologies or procedures used to assess the mechanical properties of soils is given below:

- Measures based on absolute or relative soil density are widespread. Soil density measurements are easy to make in the laboratory and a large number of correlations for different types of soil are available with various strength and modulus properties of soil. Soil density in the field is not as easy to measure since soil samples are always disturbed and it is difficult to measure accurately the in-place volume from which a soil sample has been removed. Proctor density and relative density measurements provide laboratory reference states to which in-place soil densities can be compared. In-place soil densities are measured using simple techniques such as sand cone measurements and, more recently, using nuclear density measurements. Sand cone measurements are labor intensive and prone to volume measurement errors in granular soils. Most importantly, for compaction control, the results from sand cone measurements are not available until soil moisture content is available and this means that unsatisfactory compaction work may have been covered by other material before it is rejected. Nuclear soil measurements require an expensive measuring instrument and trained operators because of the radioactive source used. Measurements are available quickly but periodic calibration measurements using a direct technique such as the sand cone are often used to increase the accuracy of the technique.

- The Blow Count (N-value) records the number of blows to drive a soil sampling tube 12 inches through the ground. This value is related to the structural properties of the soil. Its usefulness is greatly enhanced by the large amount of data available in all types of soils and the extensive empirical correlations that have been made to many other soil properties for different types of soil. The technique is not suitable for compaction control and would only be useful for post-construction evaluations in deep compaction projects.

- Static cone penetrometer site investigations involve forcing a cone-shaped tip through the ground. Measurement s made at the tip can include tip resistance, shear resistance on the side of the cylindrical base of the cone, and pore pressures at the cone tip and further back along the base. Geophysical measurements can also be incorporated into the procedures using seismic transmission between the tip and the ground surface. Cone penetrometer investigations provide a large amount of information about soil zonation and properties but are not applicable to shallow compaction control and are not used in the kinds of granular materials that are usually specified as part of road base construction.

- The pocket cone penetrometer is a surface indentation cone that provides soil strength information. The area of soil to be tested must be exposed for the measurement to be made and the technique is intended for use principally in cohesive soils.

- Vane shear tests provide field data on the shear strength of a soil. A set of vanes on a shaft are pushed into the soil and rotated causing a cylindrical-shaped shear failure surface in the soil. Only small volumes of soil are tested.

- The dynamic cone penetrometer (DCP) consists of a rod with a striking surface at its midpoint and a pointed tip. A sliding weight is lifted along the upper part of the rod and dropped onto the striking surface driving the rod into the ground. The penetration of the rod relative to the ground surface is measured on an adjacent scale. From the measurements, a plot of penetration resistance can be derived. This data indicates the depths and relative strengths of the different soil layers. The device is simple, fairly rugged, inexpensive and transportable. Correlations have been developed with some other engineering parameters and the most common in the U.S. is with the California Bearing Ratio (CBR). The device is described further in MnDOT (1993). The method is applicable to shallow site investigations and to compaction control and is also applicable to all types of soil. Measurements are not rapid but the results are available immediately.

- Plate bearing tests on exposed surfaces provide a close approximation of the information needed for spread foundation design and for quasi-static loadings on roadway pavements. The depth of soil investigated depends on the size of the bearing plate and sufficient reaction must be available to apply loads high enough to begin to fail the soil. Scale effects between small plate tests and large foundation response are a problem. Plate bearing tests typically measure the static response of the soil and may not predict the dynamic response of soils to rapid loadings and unloadings present from moving truck traffic on roadways.

- Purpose-developed compaction monitoring systems (e.g. Dynapac) may consist of an accelerometer mounted on the vibrating drum of a compaction roller connected to a data recording and analysis system. The accelerations measured on the drum are related to the impact forces of the drum on the compacted ground and hence to the stiffness of the ground. The data analysis converts the measured accelerations to a compaction meter value displayed on an indicator on the driver's platform and is stored for analysis of the compaction value and position of weak zones. Correlation to compaction specifications normally is carried out using a test surface for each compaction job.

- Another form of compaction monitor consists of a disposable sensor placed in the bottom of the hole to be compacted and connected by cable to the monitoring unit. The initial depth of the unfilled hole is measured with a built-in rangefinder in the base of the unit. As each layer is tamped, the signal received by the sensor changes with the degree of compaction achieved and is compared to pre-programmed soils data. Feedback is provided to the operator as to when to stop tamping each layer. When the hole is fully backfilled, a hammer and striker block is used to send a seismic signal to the sensor and allow a wave velocity measurement to be made. This velocity can be compared to reference velocities either from a test mold or from previous experience. The original sensor is disconnected and left in the hole. A link to Proctor Density is made using the test mold and comparing seismic velocities and measured densities.

- The Clegg Impact measurement system consists of a hammer dropped manually onto a 150mm diameter plate in contact with the ground. Different weights of hammers are used for different applications. The peak deceleration is measured which represents a force versus penetration and is a measure of the stiffness of the underlying material. This value has been correlated to California Bearing Ratio (CBR) and Young's modulus for the soil. The test takes about a minute to perform. Uses of the method include roadway base compaction tests, surface hardness and rebound of turf surfaces, and trench backfill tests. The method was developed in Australia by Dr. B. Clegg at the University of Western Australia.

- The falling weight deflectometer is used in road pavement analysis. The method consists basically of measuring the profile of the deflection basin caused by a falling weight. The depth and properties of road base layers can be inferred from the measurements using elastic layered media analysis. The properties measured relate to dynamic loading conditions.

- Various other compaction or soil property measurement devices involve tracking a parameter that relates to the mechanical transfer of compaction energy into the ground. This parameter changes as the soil beneath the device is compacted and is used as a compaction control. Typically, the imposed loads are dynamic or the compaction energy itself may be used as the energy source.

- Seismic vibration sources can be used to measure the mechanical impedance of surface layers to the imposed vibration. The power and frequency used affect the depth of soil for which the inferred properties are applicable. The use of variable frequencies allows better interpretation of soil characteristics. Seismic velocities in the soil are related to dynamic soil moduli for the soil and hence it is possible to interpret dynamic soil moduli directly from this type of measurement. Dynamic soil moduli are important for the response of pavement systems to transient loadings but are not so useful for estimating the response of soil layers to long-term loading.

- Seismic Analysis of Surface Waves (SASW) is a technique in which the speed of propagation of surface waves is interpreted to provide information on the depths and mechanical properties of surface soil layers. The use of different frequencies of excitation provides a dispersion curve in which the apparent velocity of the surface waves changes with frequency. This change in apparent velocity is caused by the varying depth of soil impacted by the different frequency signals. The soil layering and layer properties are found by inversion of the controlling equations or by an iterative analysis that attempts to provide closer and closer matches to the observed behavior. The equipment to make the measurements has become invcreasingly portable and the measurements quicker to make but the analysis remains computer intensive. It should be possible to provide rapid results with the method by using pattern matching techniques or with sufficiently powerful field computers.

Chapter 3
Application Issues

3.1 Advantages of Seismic/Impact Techniques

The principal advantages of the use of seismic/impact techniques to measure near-surface soil properties are:

- with progressive improvements in signal processing and analysis, results are now available almost instantaneously (as compared to results from sand cone tests which are not available for a day)
- the equipment can be highly portable and does not need a radiation source (as compared to nuclear density tests)
- safety of personnel taking density measurements should be improved (they are vulnerable to site traffic incidents while making sand cone measurements)
- the tests can often be adjusted to measure the average properties of different depths of soil
- the tests may allow a direct measurement of the dynamic modulus of the soil which is important in pavement response to traffic loadings

3.2 Disadvantages of Seismic/Impact Techniques

- The interpretation of seismic velocities from arrival times of compression, shear, or surface waves is not always straightforward. Waveforms may not be crisp, electrical noise in circuits can obscure waveforms, and waveforms from different reflections may overlap.
- The use of seismic analysis to interpret soil layering and layer properties often involves the inversion of the controlling equations. This introduces concerns about the uniqueness of the results -- whether two different physical conditions could produce a similar output in terms of the measured seismic parameters. When the general soil configuration is known and simple this should not be a problem.
- The attempt to resolve field data into uniform layers of soil with different properties may not relect the real variations in layer thickness and localized soil properties present in the soil.
- Use of the methods in the past has required a fair degree of understanding of the nature of the analyses and their potential problems in order to understand field problems or apparently anomalous results.
- Until recently, the signal processing required in some of the methods was not conducive to field use and rapid interpretation of results and the equipment was not rugged enough for long-term use in conjuction with compaction equipment.

3.3 Adoption of Techniques in Practice

There would be a number of benefits to the compaction process from successful, easily-implemented, and cost-effective techniques for the rapid determination of the the properties of compacted materials. These are:

- Compaction energy can be concentrated on surfaces that need it most
- No unnecessary compaction on finished surfaces
- Undercompacting and overcompacting reduced
- More complete quality assurance documentation provided as part of the process
- Better homogeneity in the compacted material
- Lower cost and risk for the contractor and owner
- Less callbacks
- Eliminates or reduces need for separate contractor to measure densities
- Can reduce acceptance delays
- Properties such as strength, stiffness can be determined though correlations
- More rapid feedback on acceptability of the work so that defective work can be corrected before it is covered up
- Assesses more directly properties of interest in the stress/strain response of soils such as elastic modulus
- Assesses more directly the effect of moisture changes on the structure of the soil as well as maximum compacted dry density (i.e. wet of optimum vs. dry of optimum compaction)

The techniques could be used for verification and control of compaction as one of a suite of methods available such as sand cone density, nuclear measurement and the dynamic cone penetrometer. The users would be road construction authorities and also contractors. The contractors need quick feedback on the acceptability of their compaction techniques to avoid costly overcompaction and even more costly undercompaction (which must be redone when the results of the density tests are available). Compaction equipment manufacturers might also be interested now that the instrumentation and computer equipment is rugged enough to be placed on the excavation equipment.

The goal of improved methods in determining the mechanical properties of compacted soils is described in the following excerpt from the Clegg Newsletter (1976):

> *It should be recognized from the outset that the logical objective of compaction is not in fact an arbitrarily selected density. The primary objective is the attainment of a certain minimum strength or compressibility (and sometimes permeability).*
> *One of the main practical advantages was that field dry density as a soil property was independent of moisture content (although moisture content was crucial to the level achieved by the compaction process). On the other hand, strength was dependent for a given soil on both density (degree of packing) and moisture content (pore water pressures).*

The use of a strength measurement for compaction control has in the past been by means of various types of penetrometers, bearing tests and falling weight devices. More recently, wheel load deflection measurements by the Benkelman Beam have been added to proof rolling procedures. Also devices have been fitted to rollers to monitor the ground stiffness. With all of these methods, the difficulty lies in the selection of appropriate value to be achieved be it in terms of compaction effort, relative compaction, penetration resistance, deflection, etc. However, it is evident that an in-situ strength measurement in some form for compaction control is desirable and is being sought after.

The unfamiliarity of some of the newer methods is addressed by El-Telbany et al. (1996).

The use of shear wave velocity measurements for subsurface characterization in geotechnical engineering has increased in popularity over the last 10 years. However, because the technology and theory for seismic measurements is from the area of geophysical expoloration, many basic, but very important factores are overlooked simply because they are outside of the realm of engineering. Even when the knowledge is available, the difficulty then becomes how to account for the factors, and determining whether the factors make a difference at all. Consequently, while many engineers have shear wave velocity data, they may be unsure of how accurate the measurements are, and hence may be reluctant to use seismic measurements.

There are other problems in using the techniques that occur to varying degrees in the newer methods. For example, techniques involving surface or near-surface mechanical responses to loadings are affected by the drying of surface layers before testing which can change the mechanical response of small surface test loadings or soil surface impacts differently than in the case of larger scale real loadings. When dry density is used as the control parameter, this is not a problem. Also, interpretation of variable results can be difficult. Many techniques depend on correlations for their interpretation that vary with soil type. If the database used to establish the correlations is insufficient, or if local soil variations occur it may be difficult to interpret the results of the measurements. This problem is noted, for example, by Laymon and Miele (1996):

One problem that hinders geophysical work and the proposed approach is the site specific issues that surround the usefulness and success of the various geophysical techniques.

More general application issues that apply to any new technique representing a capital investment or a radical change of working are:

- Will the cost of the instrument be paid back for the party that purchases it? This is a multi-faceted question since the new instrument can be purchased by an owner, contractor, compaction equipment manufacturer, consultant or specialist testing firm. The developer of the new testing system needs to convince one or all of the parties that the purchase of the system will result in a benefit for them.

- The owner can benefit from the improvements in performance of the compacted fill or from reductions in cost for the same quality. In order to achieve this the owner needs to adjust the contract specifications so that the new technique will be used for compaction control rather than just an add on test. If the owner requires that a contractor use the new system for compaction control, they take on additional liability if the new technique does not produce the expected results.
- The contractor can benefit directly if it can be shown that use of the system will allow less overcompaction and less call backs for undercompaction -- even if the contractor pays for the system entirely themselves -- as long as the extra costs of purchasing and operating the system are less than the expected savings.
- Equipment manufacturers may purchase a compaction control system for use with their equipment but this is usually a buyer option and again the contractor will need to be convinced of its benefit. It is reported that in Europe compaction control systems are more frequently used on compaction equipment than in the U.S. even though the systems are also available for purchase in the U.S. Differences in their use are attributed to the relative size of contracts, relative cost of labor, and relative levels of training and faith in the equipment operators (Geistlinger, 1996).
- Consultants will only benefit directly if the owner agrees to compensate them for testing using the new system but consultants may also be instrumental in convincing the owner that use of the technique is of benefit to the owner -- either in direct cost, quality, or reduced risk of litigation. Consultants also take on liablity when they specify a new system that is not accepted current practice.
- Specialist consultants can overcome the problem of having a high cost of equipment that is only used occasionally by a general consultant or testing firm and can provide a specialist knowledge in the use of the technique. The specialist consultant has an added difficulty in developing a market in that their work may reduce the level of services provided by a firm that will be involved in deciding to use the technique.

Clearly, even when a system provides a clear benefit, there can be many barriers that delay its adoption. There are many examples of technology changes that seem to have taken a long time to be adopted in the U.S. even when they had been in use overseas for many years. Use of the New Austrian Tunneling Method (NATM) and the use of concrete tunnel lining segments are examples from the underground construction field. If the techniques have merit and the developers individually or collectively have the staying power to continue to develop the market and overcome market objections, the techniques will slowly find their way into practice.

Chapter 4
Conclusions

The purpose of this review was to try and understand why rapid methods of soil property determination suitable for compaction control have been around in principle for several decades and yet have not won widespread adoption. Further, it was to speculate if continuing changes in the technologies would result in the methods becoming more widely used and in turn improve the quality and cost-effectivenss of compacted fills.

The conclusion of this review is that the methods continue to show promise and progress in adoption. On the other hand, it has not been surprising that they have not won widespread use as yet. There have been major technical difficulties in terms of variable or difficult to interpret results that depend on local site conditions, there is the potential loss of connection to the large database of experience and correlations available for traditional methods of assessment, there has been a specialist knowledge required that may not be present in the companies that do the current testing, and the field equipment has often not been rugged enough or powerful enough to provide real-time on-site results.

It appears that these problems are slowly being resolved and that adoption of the techniques is gradually occuring -- faster in Europe than in the U.S.

Faster and more widespread adoption will most likely come from the desires of owners for better compaction control or from contractors for better cost control in meeting compaction specifications. The use of the systems will likely accelerate once they are in moderate use because of greater familiarity with the benefits of using the systems, the reduction in liability that occurs with increasing use, and the increasing confidence that would develop in interpreting the results of the measurements and relating them to the accumulated experience in the performance of compacted fills.

The methods are not likely to be a panacea for compaction control, and may need continued refinement but, as with nuclear soil density measurements, they offer benefits of rapid results, more complete areal coverage of compaction quality and information on the dynamic mechanical properties of in-place soils.

The ability of the methods to measure dynamic soil moduli directly is a benefit for transient loading conditions such as in road pavement design but much more will need to be done to tie the results of these measurements to the actual performance of roadway pavements before the benefits of this additional knowledge will be realized. The increasing use of mechanistic analyses of pavements in design and pavement evaluation (the falling weight deflectometer, for example) will accelerate this adoption.

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