Development of a Laser-Based High Speed Deflectograph

Danish Road Institute
Report 97
1999
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This report contains a paper written in part by an author from the Road Directorate. The paper was prepared for and presented at the third international symposium on Nondestructive Testing of Pavements and Backcalculation of Moduli held in Seattle, Washington, USA on 30 June and 1 July, 1999. The symposium was sponsored by the American Society for Testing and Materials (ASTM).

The paper, which was presented by the first author, describes the development of a new high speed device for nondestructive measurement of pavement bearing capacity. The High Speed Deflectograph is laser-based and performs continuous bearing capacity measurements at all driving speeds in the range from 20 to 70 km/h. The paper describes the background for the development of the device, its measuring principle, as well as the theoretical background for the interpretation of results.
Today’s heavily congested highways provide a difficult setting for bearing capacity measurements using stationary equipment like the FWD resulting in a situation which is dangerous to both drivers and FWD operator. Furthermore, techniques like the FWD method only provide information in discrete points that are often separated several hundred metres apart. To overcome these deficiencies a laser-based high speed deflectograph is being developed which can perform continuous bearing capacity measurements at all driving speeds in the range 20-70 km/h.

The unique concept of the high speed deflectograph utilizes laser Doppler sensors to provide the deflection speed of the pavement surface. By using this technique the deflection speed is determined in one operation as opposed to the more commonly used distance laser sensor method which determines the deflection as the difference between vertical deformation in two different points. The laser Doppler system has been found capable of determining deflection speeds within the desired range of driving speeds with an accuracy of 0.14 mm/sec, which has been shown to correspond to an accuracy of the deflection of 5 µm.

While it is important to measure deflection speeds correctly, it is equally important to continuously register and control the position of the laser sensors using secondary measuring systems like servo systems and inertial units.

The high speed deflectograph consists of a towing truck and a trailer on which the laser sensors are mounted. The trailer is equipped with a system, which allows variations of the applied load.

In parallel with the development of the physical measuring device a study is carried out concerning the interpretation of results from the high speed deflectograph. Results from work carried out to establish a coupling between deflection speeds and absolute deflections, of which the latter can be compared to FWD results, are presented.
Introduction

During the period from 1983 to 1996 traffic work carried out by cars on roads in Denmark increased by 47% corresponding to an annual increase of 3%. In the same period the increase of traffic work carried out by cars on motorways approached 350%. On motorways the traffic work carried out by trucks increased by 165% from 1983 to 1996 (Danish Road Directorate 1998). This constitutes a difficult setting for stationary pavement condition measurements like the falling weight deflectometer (FWD) test, and potentially dangerous situations for both drivers and FWD operator may easily occur. Furthermore, a stationary test only provides information on pavement condition in discrete points, which are often separated several hundred metres apart.

As part of the national Danish road administration, Danish Road Institute has a need for safe and efficient pavement condition measurements, and hence the institute in 1996 initiated the development of a high speed deflectograph, which should be able to monitor the bearing capacity of pavements at all driving speeds in the range 20-70 km/h.

The main object of the project is to develop a new laser based device, which can measure the bearing capacity characteristics of a highway pavement at the speed of traffic. Since the project involves new technology it was already from the outset decided that interpretation of results from the new device be given high priority, and that an analysis method aimed directly at the new device be developed.
Nondestructive Pavement Testing in Denmark

In 1972 Danish Road Institute started the development of its first travelling deflectograph capable of carrying out continuous measurements with a Benkelman beam. The first deflectograph was used until 1988 when a second-generation deflectograph was developed and put into daily operation. The new deflectograph was used routinely for measurements of relative bearing capacity on the national highway network in Denmark until 1991. Since 1991 Danish Road Institute has exclusively used its three FWDs for network and project level measurements of the state highway network in Denmark.

The two deflectographs used the same basic principle for measurements as they monitored the deflections of two Benkelman beams positioned in the wheel paths in front of the rear wheels of a semitrailer. Compared to the first deflectograph, the second was able to carry out measurements while driving in curves, it could perform measurements at a driving speed of 6 km/h (six times faster than with the first deflectograph!), it was operated by one person, and it made use of computer technology for data acquisition and for real time plotting of results (Jansen 1990). The new deflectograph was built as a truck-semitrailer vehicle as shown in figure 1.

The deflectograph measured the deflection for each nine metres with an accuracy of 10 \( \mu \)m with a reproducibility of 98% (Jansen 1990), and on the basis of the measured deflection as well as the traffic load, the relative bearing capacity could be determined. Good relative bearing capacity was interpreted as equal to at least ten years of remaining structural lifetime for the pavement. Using the diagram in figure 2, the condition of the national highway network was classified into three structural categories, and pavement sections with poor or fair relative bearing capacity would undergo more detailed evaluation with a FWD. Although a relation between deflection from the deflectograph and subgrade modulus was established it was never successfully proven that results from the deflectograph deflection bowl could be utilized to gain information on the structural condition of pavement layers.

Figure 1.  Danish Road Institute's Second Generation Deflectograph (Jansen 1990).

Figure 1.  Diagram for Estimation of Relative Bearing Capacity (Jansen 1990).
Mainly because of its very low driving speed the deflectograph was difficult to discern from a holding vehicle, and twice within a period of few years the second deflectograph was hit by passing vehicles. The last collision was fatal to the driver whose truck crashed into the deflectograph and as a consequence of the accidents the deflectograph was never used again.

From 1991, FWDs have been used to monitor the bearing capacity of the state highway network as well as lower classified roads. In 1994 the three FWDs of Danish Road Institute covered 6 200 km. Measurements for the pavement management system covering the national highway network are carried out on sections expected to have a remaining structural life time less than five years and on newly overlaid sections (European Commission 1997).
Background for the Development of a High Speed Deflectograph

Since the use of the deflectograph ceased in 1991, Danish Road Institute has been looking for a means other than the FWD to perform a preliminary screening of the national highway network with regard to structural pavement condition. During the last decade several very interesting projects have emerged to offer automatic, continuous deflection measurements by the use of laser sensors. Two of these devices are capable of performing measurements at or near traffic speed. Development of the Swedish rolling deflection meter began in 1991 with a prototype and later a new version of the device was built, which was ready for test measurements in 1998 (Lenngren 1998). The Swedish device is based on the measurement of an un-loaded and a loaded cross profile under a truck. A number of distance measuring laser sensors register the two cross profiles, and the deflection caused by the wheel load is determined as the difference between the two profiles. The device is capable of performing measurements at driving speeds up to 70 km/h.

Another equipment is the rolling weight deflectometer (Johnson and Rish III 1996), which also measures pavement deflections caused by a moving wheel load. Deflections are registered using distance measuring lasers located near the loading wheel and at three points in front of the wheel. The device was developed for airport pavements, but a modified version for highways has been proposed which should be able to carry out deflection measurements at a driving speed of 50 km/h.

In the middle of the 1990s neither of the devices mentioned seemed ready for production testing, so when presented with a new concept for high speed bearing capacity testing by Greenwood Engineering, Danish Road Institute decided to establish a project with the aim of developing a new laser-based high speed deflectograph. The project, which comprises equipment development and construction as well as development of a theoretical framework for the interpretation of results from the device, started in 1996 and is expected to be finalized in March 2000. Main partners in the project are Danish Road Institute and Greenwood Engineering, while Delft University of Technology in The Netherlands and The Technical University of Denmark are engaged in the theoretical work in co-operation with the main partners.

The new device, which will be described in the following sections, uses the semitrailer of the second deflectograph, which applies an axle load of ten tons. The trailer provides good opportunities with regard to testing of different design solutions. Hence, the length of the trailer can be varied between eight and twelve metres, thus allowing tests to determine the distance from the rear wheels of the towing vehicle to an un-loaded location in front of the wheels of the trailer. Results from the Danish accelerated pavement test facility indicate that this critical length is 2-4 metres (Macdonald and Zhang 1997).
Principle of the High Speed Deflectograph

The high speed deflectograph is based on the idea of measuring the velocities of deflections rather than the absolute deflections.

The Doppler Principle
In 1842, the Austrian physicist Christian Johann Doppler noted that the wavelength of light, sound, or any other kind of propagating energy measured by a moving observer will be shifted by a factor of \((v/c)\) such that:

\[
F_{\text{Doppler}} = -F_{\text{source}} \cdot \frac{v}{c}
\]  

(1)

where:

- \(v\) = relative velocity between source and receiver
- \(c\) = speed at which the wave propagates
- \(F_{\text{Doppler}}\) = change in frequency at the receiver
- \(F_{\text{source}}\) = the transmitted frequency (Hunt 1987)

If the object moves (slower than the wave speed), the wave fronts ahead of the object emerge closer together than the in static case while the wave fronts behind are farther apart. This is the Doppler shift; if the object is approaching, the transmitted wavelength is reduced, but if the object is receding the transmitted wavelength is increased. Consequently, light from moving objects will appear to have different wavelengths depending on the relative motion of the source and the observer. The Doppler shift is illustrated in figure 3. Observers looking at an object, which is moving away, see light which has a longer wavelength than it had when it was emitted (a redshift), while observers looking at an approaching source see light, which is shifted to a shorter wavelength (a blueshift). The reason why only the Doppler shift of sound is noticed, is a consequence of the tremendous difference in the speeds of sound and light.

Figure 3. Doppler Shift (Wright 1999).
Principle of Measuring System
A number of laser Doppler sensors are mounted on a heavy vehicle. The laser rays emitted from the sensors are incident on the road surface and the sensors measure velocities in the direction of the laser rays.

![Diagram of Measuring System](image)

The load will cause the pavement surface to deflect and the sensors register the velocity of the movement. The sensors are mounted on a rigid steel beam in front of one wheel as illustrated in figure 4.

When conducting deflection measurements using distance measuring techniques, it is necessary to register data both before and after the load has been applied to the pavement. Measuring the deflection velocity holds the advantage that the procedure has only one step, which means that measurements in curves do not constitute a problem. Besides, the velocity of the deflection is likely to increase with increasing driving speed, which makes the concept suitable for conducting measurements at high speeds.

Apart from collecting deflection velocity data from the laser Doppler sensors, a number of other measuring systems need to be implemented. The laser Doppler sensors measure the difference in velocity between the sensors themselves and the pavement surface. Thus, the movement of the sensors has to be measured and filtered away from the deflection velocity output. Furthermore, since the velocity is measured in the direction of the laser rays, the incident of the laser rays on the pavement should ideally be exactly perpendicular. If the incident is not perpendicular, a component of the driving speed will be registered as part of the measurement. Calculation of the magnitude of the component of the driving speed requires the angle of incident to be measured accurately along with the driving speed. The movements of the laser Doppler sensors and the angle of incident are measured with an inertial unit comprising three accelerometers and three fiber gyros. The driving speed is measured using an odometer.

Movement of the laser Doppler sensors is limited and controlled by a servo system on the mounting beam to ensure that the laser sensors are focused at all times. Input data for the servo system is provided by the inertial unit and one distance measuring laser.
sensor in each end of the mounting beam. Finally the pavement surface temperature and the applied load should be measured in order to provide a complete basis for the interpretation of the data with respect to bearing capacity evaluation. The block diagram in figure 5 provides an overview of the system.

Figure 5. Block Diagram Containing the Measurement Systems of the High Speed Deflectograph.
The accuracy of the velocity measuring laser sensor is essential for the concept of the high speed deflectograph to be successful. The feasibility of the laser Doppler method was evaluated by a test of the accuracy of the sensor, which considered the fact that the noise level in the signal from the sensor increases with increasing driving speed.

A test set-up for evaluation of the accuracy of the velocity measuring laser sensor was built and consisted of two measuring systems: The laser Doppler sensor and a reference. The reference instrument was an optical linear encoder. Two mechanical systems were applied: an asphalt disk for the simulation of a pavement surface and a system for simulating the deflection of the pavement surface. The latter was done by moving the laser Doppler sensor in the direction of the laser rays. The principle of the accuracy test is illustrated in figure 6.

A test was conducted by rotating the disk corresponding to a driving speed of 20 m/s (equal to 72 km/h). The laser Doppler sensor was moved on the rail guide at approximately 10 mm/s. Collection of data from both the sensor and the reference started simultaneously when the laser sensor was in an optimum distance from the surface. Velocity data from the laser sensor contained two contributions as shown in figure 7: from the movement of the sensor as well as from the fact, that the incident of light on the asphalt disk was not exactly perpendicular.
Figure 7. The Rotational Speed of the Disk and the Angle of Incident Influences the Velocity Measurement.

The magnitude of the contribution from the asphalt disk depends on the speed of rotation and the angle of incident of the laser rays on the disk. This is described by the following simple formula:

\[ V_m = V_b + V_k \cdot \sin \alpha \]  \hspace{1cm} (2)

where:

- \( V_m \) = measured velocity
- \( V_b \) = velocity of the movement of the sensor
- \( V_k \) = simulated driving speed (by rotation of the disk)
- \( \alpha \) = angle of incident

The mean values of the measured velocities from both the linear encoder and the laser sensor were calculated and the difference between the results from two systems was determined. Next the standard deviation of the results was calculated and interpreted as a measure of the accuracy of the sensor.

The result was a standard deviation of 1 mm/s. The duration of the measurements that formed the basis for this result was 10 ms because of limitations in the data processing hardware. If the duration of a measurement is e.g. 500 ms corresponding to a driving distance of 10 m, the accuracy would be 0.14 mm/s. In order to evaluate the result with respect to the feasibility of using the laser Doppler sensor for deflection measurements the result was transformed into absolute deflection.
Interpretation of Data

With the purpose of showing how the velocity data can be transformed into absolute deflections by integration, data from deflection bowls measured with a FWD was used.

![Polynomial fit to FWD data from highway](image)

Figure 8. Sixth Order Polynomial Fit to Deflection Data Obtained with FWD on a Highway.

The shapes of the deflection bowls were determined by polynomial fitting and figures 8 and 9 show an example of a 6th-order polynomial fit to data obtained with a FWD on a highway pavement along with the residuals of that fit.

![Residuals](image)

Figure 9. Residuals from Polynomial Fit. All Residuals are Less than 1 µm.
The deflection bowl based on the polynomial fit as well as the first derivative of the deflection bowl (the deflection velocity) are drawn in figure 10.

![Polynomial fit and deflection velocity](image)

Figure 10. Polynomial Fit and Deflection Velocity at 20 m/s Driving Speed.

The above shows how it is possible by integration to transform deflection velocity data into a deflection bowl (with knowledge about the shape of the bowl, here 6th order polynomial fit). To perform the procedure described in practice it would thus be necessary to use at least five laser Doppler sensors. Data from each sensor provide information about the slope of the deflection bowl at the point where the sensor measures. Locations in the deflection bowl between sensors will therefore have to be estimated. The use of the 6th order polynomial fit procedure is thus an example of how the data could be interpreted. How the data are eventually to be interpreted is the subject of further research.

With the accuracy of the laser sensor, \( \varepsilon_{\text{velocity}} \), equal to 0.14 mm/s as shown in the previous section and a driving speed, \( V_k \), of 70 km/h (=20 m/s), the accuracy of the measurement of the slope of the deflection bowl, \( \varepsilon_{\text{slope}} \), will be:

\[
\varepsilon_{\text{slope}} = \frac{\varepsilon_{\text{velocity}}}{V_k} = 7 \mu m/m
\]  

(3)

To calculate the accuracy of the absolute deflection, \( \varepsilon_{\text{absolute}} \), the length, \( L \), over which the integration takes place must be included. The number of laser sensors, \( N \), is included as a factor \( \sqrt{N} \), because it is reasonable to assume, that the inaccuracies of all the sensors do not point in the same direction at any given point in time. With five sensors positioned within 1.5 m the result is:

\[
\varepsilon_{\text{absolute}} = \frac{\varepsilon_{\text{velocity}}}{V_k} \cdot \frac{L}{\sqrt{N}} = 4.7 \mu m/m
\]  

(4)
If only three sensors are available they should be positioned within $L = 1.25\, m$ in order to obtain an accuracy of $5\, \mu m$. It is emphasized that this result is obtained in a laboratory test and concerns the accuracy of the laser Doppler sensors only. The overall accuracy of the system will depend on the accuracy of the supplementary systems, the number of laser sensors employed, their position and their performance in the field as well as how the data is postprocessed. Investigations into the accuracy of the supplementary systems suggest that the overall accuracy can be maintained at the order of magnitude mentioned. However, several different configurations of the device are possible, each with a different accuracy and price.

The best signal, i.e., the largest deflection velocity, is located where the slope of the deflection bowl has its maximum. In order to investigate the location of optimum positions to mount the laser sensors, the computer program Veroad was used to simulate deflection bowls from moving loads. Veroad calculates displacements, stresses and strains for pavements modeled as multilayer structures taking into account the visco-elastic properties of asphaltic materials. The load is modeled as a moving wheel defined by moving speed, radius of a circular contact area and vertical contact stress. Pavement response can be calculated at several depths in the structure, and several surface positions can be specified.

The position of the maximum slope in the deflection bowl is located under the wheel. The Veroad simulations showed the optimum position to depend more on the type of pavement than on the type of load. Since the pavement is the unknown factor, caution should be taken not to overinterpret the results. It should also be emphasized that the Veroad program is not verified for driving speeds greater than 10 m/s (Oost and Hopman 1995). The position of the maximum slope in the deflection bowl changes as the driving speed changes. It is the intention to use two laser Doppler sensors for the high speed deflectograph prototype and with only one sensor present in the deflection bowl it is therefore not possible to determine how the sensor is located in relation to the optimum position. This indicates that the high speed deflectograph when configured with two sensors (one in the deflection bowl and one as a reference outside the deflection bowl) can be used as a screening device, pointing out interesting places on the road network for further examination. More detailed information about the deflection bowl will require the device to be configured with more sensors.

The best overall measuring conditions are obtained using twin wheels in combination with a special mechanical-optical arrangement allowing the measurements to be conducted between the wheels, approximately 250 mm in front of the load center. If this proves unpractical, the second best option is to use super single wheels and measure next to the wheel. The expected deflection velocities using Veroad were found to be in the order of 5-10 mm/s for flexible roads and 1-2 mm/s for rigid roads, which corresponds to an expected accuracy of approximately 1.5-3.0% for flexible pavements and 7-14% for rigid pavements, respectively.
Conclusions

A new unique device for nondestructive testing of pavement bearing capacity has been presented. The high speed deflectograph makes use of laser Doppler sensors to provide a continuous measure of the deflection velocity of a pavement surface loaded by a semitrailer driven at normal traffic speed. Supplementary systems keep the laser sensors focused and allow corrections of data with regard to applied load, pavement surface temperature as well as the laser sensors’ deviations from vertical direction. A laboratory test has demonstrated that the accuracy of the laser sensor is 0.14 mm/s in the desired range of driving speeds corresponding to an accuracy in terms of absolute deflection of 5 µm. The overall accuracy of the system will depend on the accuracy of the supplementary systems, the number of laser sensors employed and their performance in the field.

The high speed deflectograph is expected to be ready for test measurements in summer 1999, and when the test period has been successfully completed the device will be used for bearing capacity screening measurements on the national highway network in Denmark thus providing a safe and quick overview of the structural condition of the network.

Further work related to the high speed deflectograph will include the development of a calibration procedure for the device. Comparative measurements with FWDs will be performed on ordinary highways as well as on instrumented pavements since a relation between the FWD and the high speed deflectograph is very important. This will allow the establishment of the necessary link to previous years’ FWD measurements as well as future project level FWD measurements. The work regarding an analysis framework special to the high speed deflectograph device is expected to continue for at least the next two years.
Acknowledgments

The development of the high speed deflectograph is supported by the Danish Agency for Trade and Industry, Ministry of Business and Industry. The Veroad program was used by permission from the Road and Railroad Department of The Technical University of Delft, Hydraulic Engineering, Division of Dutch Ministry of Transport, owner of the Veroad program.

Greenwood Engineering is applying for a worldwide patent covering the idea of the high speed deflectograph for both road and railroads.
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