Liquid Level Gauge for Measuring the Cross-Sectional Deformation of Aggregate-Surfaced Roadways

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As part of an operational test assessing the effect of tire pressure on aggregate roadway deterioration, an instrument was developed to monitor deformations of the surface and subgrade at selected cross sections. This liquid level gauge measured elevation differences with a pressure transducer and recorded field data for processing on a personal computer. Heavy-duty hoses placed on the subgrade before the test allowed the passage of the transducer housing and permitted measurement of subgrade elevations at regular intervals across the roadway. Data from this device were plotted to show cross sections of the roadway structure with a precision of 3 mm (0.1 in.) for subgrade readings and 8 mm (0.3 in.) for surface readings. Surface and subgrade deformations were evaluated at weekly intervals and before and after maintenance activities. Rut development was traced, and contributions of subgrade and surface deformations were isolated. The instrument was portable, compact, and not affected by field or environmental conditions.

Recent developments in the availability of central tire inflation systems for use on commercial trucks in the forest industries have spurred the study of road deterioration as a function of tire pressure. The USDA Forest Service has been a leader determining the effects of tire pressure on roadway surfaces. As part of this effort, a liquid level gauge was designed, constructed, and used to monitor the deformation (surface and subgrade) of several aggregate-surfaced roadways at two test sites in Washington and one in Oregon. These tests were part of a larger effort to assess the effects of tire pressure on aggregate-surfaced roadways during operational log hauling and were a continuation of testing done by others to collect this type of data (*1*).

Roadway surface profiles and cross sections have been plotted using a number of methods, usually involving some type of optical or photogrammetric survey. Vertical subgrade deformations have been monitored with vertical probe extensometers, subsurface settlement points, or differential pressure gauges (*2*). The liquid level gauge described here is of the latter type and presented several advantages that led to its selection, development, and use. Subgrade and surface measurements were electronically recorded in a consistent format transferable to personal computers and compatible with spreadsheet software. Data were collected by one person without the need of an assistant, who would have been required with rod-and-level surveys. Unlike equipment that would have been permanently installed at specific locations within the pavement structure, the level gauge allowed deformations to be monitored at any desired number of points across the surface and subgrade at the selected cross section. The method described also proved to be fast, repeatable, and insensitive to site conditions such as weather.

This paper describes the development, design, and performance of the liquid level gauge and how it was used to measure subgrade and surface cross sections on aggregate-surfaced forest roads. Examples of cross-sectional deformation under heavy truck traffic are examined to illustrate the usefulness of the liquid level gauge in evaluating roadway performance.

BACKGROUND

Surface rutting is commonly used as an indicator of the performance of aggregate-surfaced roadways and, in the case of the operational test sites here discussed, as a trigger for maintenance activities (*3*). Many procedures for the design of aggregate-surfaced roadways (*4–6*) return the thickness of surfacing material required to prevent ruts of a given depth from forming under a certain quantity of traffic. Subgrade and surface strength are often entered as California bearing ratio (CBR) values or resilient moduli, and estimated traffic over the desired life span is entered in units reflecting both the magnitude and quantity of loading (such as 18-kip equivalent single-axle loads). A design chart, program, or nomograph establishes the thickness of surface rock required to prevent a rut of greater than 25 to 50 mm (1 to 2 in.) (typically) from forming under the specified traffic. Often these models assume that the subgrade, generally the weaker layer of the two, is vertically deformed under the wheel tracks due to stresses from traffic loading. This rutting is slowed or delayed by the dispersion of bearing stresses by the stiff surface material over the weak, underlying subgrade. Surface rutting is assumed to occur as the applied surface rock settles into the depressions developing in the subgrade.

The need to evaluate subgrade deformation arose in response to this notion of subgrade rutting as the underlying cause of roadway deterioration. Another concept of roadway performance was developed that anticipated near-surface rutting under high-pressure traffic due to shearing in the applied rock and surface and subgrade rutting under low-pressure traffic due to compaction or failure under traffic. The liquid level gauge, or some functional equivalent, was required to

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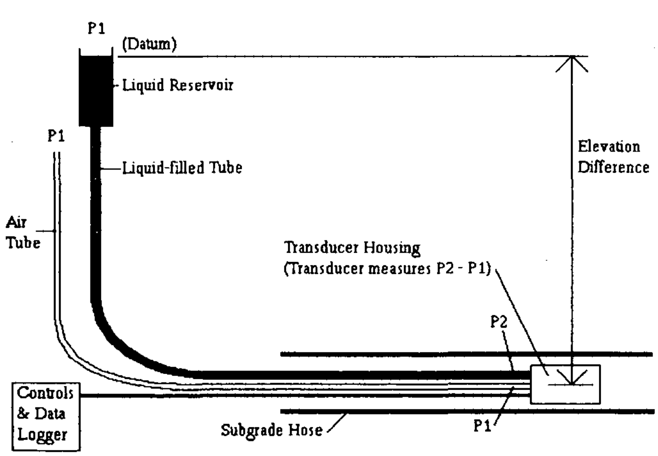
distinguish the components of surface rutting attributable to deformations occurring in the surface material and subgrade.

DESCRIPTION

The liquid level gauge consisted of a pressure transducer connected by liquid- and air-filled tubes and control circuitry to an open liquid reservoir and a data recorder. It was used to establish the elevation of points along roadway cross sections relative to a fixed reference. Surface measurements were made by placing the transducer housing directly on the road surface. Measurements on the subgrade were made by passing the transducer and its umbilical through an empty, heavy-duty hose placed on the the subgrade during roadway construction, before the application of traffic (Figure 1).

The instrument determined the relative elevation of a point on or beneath a road surface by measuring the pressure caused by a column of liquid. The height of the column was bounded by the free surface of the liquid in a reservoir and by a pressure transducer at the point of interest. The pressure was measured by a pressure transducer connected by a liquid-filled tube to the open reservoir. A second, empty tube provided an atmospheric pressure reference. By establishing the pressure difference between these two, the transducer determined the weight of liquid vertically between itself and the free surface at the reservoir. This weight was translated into a length on the basis of the specific gravity of the liquid and indicated the distance of the transducer (and the point of interest) above or below the free surface at the reservoir (Equation 1, Figure 1).

The level gauge used a solid state, piezoresistive, temperature-compensated, instrumentation-grade pressure transducer, 11 mm (0.45 in.) in diameter and approximately 41 mm (1.63 in.) long. It was sealed in a piece of thin-walled brass tubing 76 mm (3.0 in.) long with 13 mm outside diameter using epoxy. Two lengths of clear vinyl tubing, 6 mm (0.25 in.)



NOTES: 1. P1 is atmospheric pressure.
2. P2 is pressure due to weight of liquid above transducer.
3. $\text{Elevation Difference} = \dfrac{P2 - P1}{(\text{Liquid Specific Gravity})(\text{Density of Water})}$ (Eqn. 2)

FIGURE 1 Liquid level gauge.

outside diameter, terminated at the pressure transducer inside the brass housing. One length of tubing was filled with a solution of ethylene glycol in water (25 percent by weight) and was connected directly to a port on the pressure transducer. The other length of tubing was left empty and provided atmospheric pressure to the transducer. A precision thermistor was also enclosed in the brass probe housing. This allowed temperature to be recorded simultaneously with pressure, so the effect of temperature on the pressure transducer could be factored out. Electrical leads from the pressure transducer and thermistor were brought back along the tubes and connected to a readout and data logging unit. The entire apparatus was battery powered and designed to be portable (Figure 2).

The transducer was capable of reading pressure differences up to 13.8 kPa (2 psi). The liquid used had a specific gravity of 1.03 and a viscosity ranging from 0.0022 N-s/m^2 (0.46 $\times$ 10^{-4} lbf-s/ft^2) at 20°C to 0.0035 N-s/m^2 (0.73 $\times$ 10^{-4} lbf-s/ft^2) at 0°C. This liquid-transducer combination gave an elevation difference range of 1.66 m (65 in.). Calibration measurements were done each time the instrument was used so that uncompensated variations due to temperature or evaporation could be eliminated.

Mineral oil was initially used in the gauge, but the viscosity of the mineral oil (0.0331 N-s/m^2, or 6.91 $\times$ 10^{-4} lbf-s/ft^2, at 25°C) and the elasticity of the tubing seemed to cause large instabilities in the displayed readings. Readings stable to within 1.3 mm (0.05 in.) were achieved in 3 to 5 sec with the same tubing and the 25 percent solution of ethylene glycol, so the mineral oil was abandoned. Both the ethylene glycol solution and the mineral oil could withstand subfreezing to subtropical temperatures.

Before use, the tubes and electrical leads connecting the probe housing to the electronics box were taped together at 150-mm (6-in.) intervals. This made the "umbilical" easier to handle and indicated the spacing at which readings would be made in the subgrade. These tape bands were numbered beginning with zero at the probe housing.

The readout box contained power supply, signal conditioning, control, digitizing, data logging, and display components. The power supply and signal conditioning functions were provided on a single custom interface board. The control, digitizing, data logging, and display functions were performed by an off-the-shelf, battery-powered data logger. The interface board and the data logger were mounted in a single case. Field data could be uploaded directly to a desktop computer.

The data logger was configured to record several pieces of information at each reading: the date and time, a hose identification number, a position number, a temperature reading, and three elevation readings taken at 1-sec intervals. Multiple readings of the elevation were made to monitor and adjust for instabilities.

The probe housing and umbilical were designed to be threaded through a hose buried at the surface-subgrade interface to track deformations at that level of the roadway structure. Hydraulic pressure hoses [38 mm (1.5 in.) outside diameter; 25 mm (1 in.) inside diameter] with single- and double-braid steel reinforcement and wire-reinforced hydraulic suction lines were tested for resiliency by rolling over them with a pickup truck and a steel-drum roller. On the basis of observations, the suction hoses were eliminated.

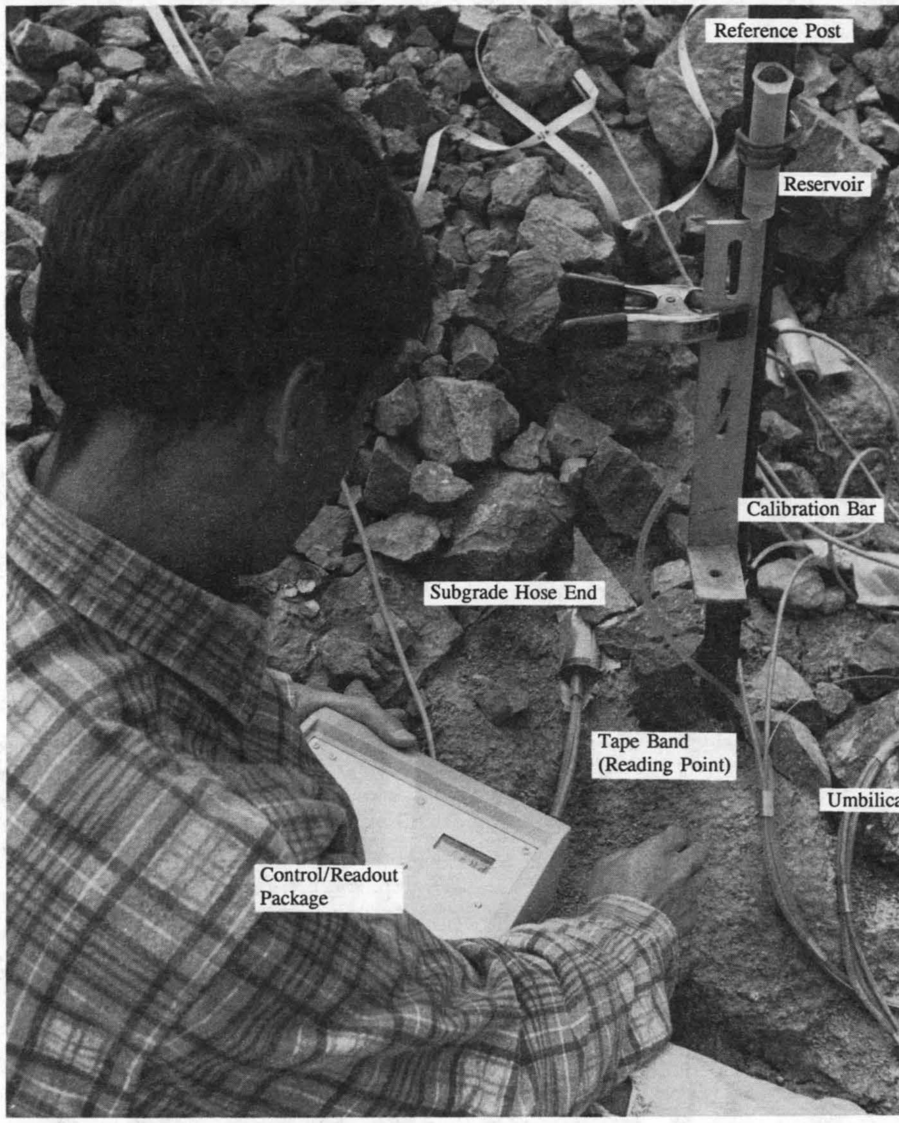


FIGURE 2 Liquid level gauge in use.

FIELD INSTALLATION

Sections of hose 6.4 to 7.3 m (21 to 24 ft) long were placed across the roadway at points of interest. At one test site, they were laid on top of the prepared subgrade, staked down, and covered when the road was ballasted. At a second site, since the surface rock had already been placed, trenches were dug across the road down to the subgrade, hoses were placed, and the trenches were backfilled and compacted. Lengths of twine were threaded through the hoses and left there to pull the probe and its attached tubes and wires into position to make a set of readings. Subgrade hoses were kept capped during installation and between readings.

Steel fence posts were driven into the ground in line with and about 0.5 m beyond the hose ends to serve as supports for the open fluid reservoir of the liquid level gauge and as benchmarks. Rod-and-level surveys were done to tie together these reference stakes and to monitor overall slope stability. Notches were filed into the fence posts at about the original crown height of the road. These marks were used as reference locations for the free fluid surface in the reservoir and allowed the gauge's range to encompass both subgrade rutting and surface heaving.

PROCEDURE

The fluid reservoir of the gauge was strapped to a post adjacent to a hose end so that the fluid surface was aligned with the reference notch in the post. The probe was attached to the preplaced twine in the hydraulic hose and drawn through until it was just protruding from the opposite end. The cord was left attached so that it would be pulled back through the hose, ready to use on the next visit. Returning to the reservoir (zero) end of the hydraulic hose, an L-shaped steel bar of known length [321 mm (12.63 in.)] was clamped onto the fence post so that its upper end was just touching the base of the fluid reservoir (Figure 2).

Calibration

A set of calibration readings was made immediately before and after each set of hose readings. After entering a hose identification number (ID) and a position number to indicate that the measurements were for calibration purposes, four readings were made with the probe stationary at the opposite end of the subgrade hose and the reservoir resting alternately on the top end and bottom end of the steel bar clamped onto the fence post. In effect, the length of the bar was being measured by the gauge, so that a calibration factor could be calculated by comparing the probe-perceived and actual lengths of the bar. Experience indicated that greater stability in readings was achieved by moving the reservoir and not the probe, since the reservoir was easier to fix securely to the stake and the probe housing would be stable in the subgrade hose. Following these readings, the hose number was entered as the ID, and the subgrade readings were begun.

Subgrade

The first reading made in the subgrade was assigned a position number corresponding to the number on the umbilical at the reservoir (operator) end of the subgrade hose. The data logger was preprogrammed to assign position numbers to subsequent readings in descending order until reset. This allowed the operator to compare the hose number with the position number in the data logger and avoid missed readings. The probe was drawn through the hydraulic hose 150 mm (6 in.) at a time, with a pause at each tape band for a reading. This generally required 12 to 15 sec, allowing for the reading to stabilize and for the data to be acquired. The final reading in the subgrade was made with the probe housing at the end of the hydraulic hose nearest the reservoir and operator.

Surface

Before making surface readings, a tape measure was stretched level across the roadway between the fence posts. The first reading was made in the far end of the subgrade hose opposite the reservoir. Readings were then made at 150-mm (6-in.) horizontal intervals across the roadway with the probe housing directly on the road surface. A final reading was made with the probe at the zero end of the subgrade hose. The probe was then threaded back 0.76 m (30 in.) into the hydraulic hose, and a second set of calibration readings was made. Since some of the hose ends protruded from the ground a short distance, the readings were made back far enough in the hose to ensure that the hose was secure, but not far enough into the hose that traffic effects would be significant. These readings also served as references in case any of the fence posts were disturbed.

Data Analysis

After reading all hoses at a site, data were downloaded to a desktop personal computer and translated into a text format readable by a spreadsheet program. Data reduction involved several steps and resulted in an x-y plot of surface and subgrade profiles for a particular hose. Data were first screened for extraneous readings and errors in assigning identification or location numbers. The three elevation readings were reviewed and reduced to one: any reading that occurred twice or more was accepted, or the average of all three was accepted if no value repeated. A calibration factor for that day's readings was calculated and applied to all that day's data.

The calibration factor was found by comparing the probe-measured bar length with the actual bar length. Each pair of top-of-bar and bottom-of-bar readings represented one instrument-measured bar length, and the calibration factor for the day was the actual bar length divided by the average of all of the gauge-perceived length measurements made on that day. Multiplying elevation readings by this factor corrected gauge-perceived length to actual length. No correction of elevation readings was made if the average calibration factor for that day fell between 0.99 and 1.01.

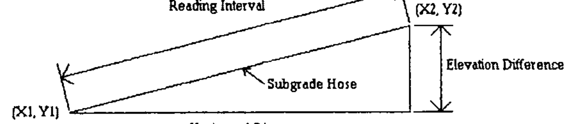
The level gauge did not measure horizontal positions. Since surface readings were taken at 150-mm (6-in.) horizontal intervals, the x-coordinate for any position was found by assigning a value of zero to the first reading. Subgrade readings were made at 150-mm (6-in.) intervals along the actual interface, and horizontal distances were calculated as shown in Figure 3. The x-coordinate for any subgrade reading was calculated as the sum of the horizontal distances between readings to that point, assuming a zero value for x for the first reading.

Subgrade elevations were interpolated at horizontal locations corresponding to the locations of surface readings. This eased the calculation of surface thickness and cross-sectional area and provided consistent points whose elevations could be tracked over time at both the surface and subgrade. A sample data plot is shown in Figure 4.

PERFORMANCE

Repeatability

To evaluate the repeatability of readings of the gauge, four sets of subgrade and surface readings were made at Hose 35 at the Vail, Washington, test site on May 22, 1992. These were preceded and followed by rod-and-level measurements of the surface at that location. The results of this field trial are given in Table 1. The precision of the level gauge was estimated as 8 mm (0.3 in.) for surface readings and 3 mm (0.1 in.) for subgrade readings on the basis of the difference



$$\text{Horizontal Distance} = [(\text{Reading Interval})^2 - (\text{Elevation Difference})^2]^{0.5} \qquad \text{(Eqn. 3)}$$

FIGURE 3 Calculation of horizontal distance between readings.

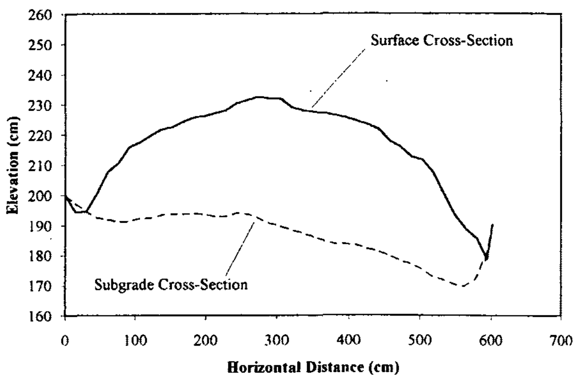


FIGURE 4 Sample data plot (Hose 12, June 7, 1992).

two-sigma limit (D2S) as recommended by ASTM C670 and E177 (7).

Readings made at the subgrade were quite variable near the ends of the hose. At this location, the hose ends protruded some distance beyond the ground surface and were able to flex and deform significantly. Readings adjacent to the hose ends ranged up to 70 mm (2.8 in.), whereas readings made 0.75 m (30 in.) or more in from the hose ends ranged over 5 mm (0.2 in.) or less. Because of this, and the variability in surface roughness across the road surface, readings within 0.75 m (30 in.) of the hose ends were excluded in estimating precision. The precision of the probe for subgrade measurements would have been improved if a satisfactory means had been found to keep the probe housing centered or resting securely within the subgrade hoses. Efforts to find satisfactory means were unsuccessful.

The repeatability of surface readings was highly dependent on the nature of the surface rock. The roads evaluated during this operational test were constructed with pit-run shot rock with a size range from fines up through 80 to 100 mm (3 to 4 in.). In the trafficked portion of the roadway, rocks were broken down and the surface was well choked with smaller particles, whereas boulders, coarse gravels, and significant void spaces were present on the shoulders. As a result, elevation readings from the central portion of the roadway tended to be more replicable than data from the edges. Readings taken at any particular point in the wheel tracks generally ranged up to 5 mm (0.2 in.), and readings at any point on the shoulders varied up to 31 mm (1.2 in.).

Surface readings made with the level gauge for this trial compared favorably with those made by rod-and-level surveys immediately before and after the gauge readings. The range of surface readings attained with the level gauge during this test was slightly higher for all positions than that achieved by rod-and-level surveys and lower than the optical method when the shoulders were excluded. The roadway cross sections as defined by the two methods were quite similar.

Temperature Sensitivity

The liquid level gauge was used on three sites from November 1991 through June 1992 in temperatures ranging from 2°C to 40°C, as measured by the thermistor in the probe housing. Calibration readings made over this period with two gauges indicate that there is a slight increase in the elevation difference measured by the probe with temperature, in spite of the compensation made by the transducer. Analysis of absolute error (AE) versus temperature (T) indicated the following:

$$AE = -0.2248T + 4.4137 \qquad r^2 = 0.5146$$

The low r^2 is mainly attributable to improper (out of plumb) placement of the steel gauge bar on the fence post or to imprecisely seating the reservoir on the gauge bar, since calibration factors tended to be consistent at any particular hose location. Over the range from 5°C to 20°C, where most readings were made, absolute error varied from roughly 3 mm (0.13 in.) down to virtually zero. This corresponded roughly to the estimated precision of the instrument.

The gauge was used in weather conditions ranging from cold, driving rain to hot sun. Provided that the electronics case was protected, the gauge's performance was not impaired. Some dramatic fluctuations in readings were attributed to wind blowing over the open ends of the air and fluid tubes, altering the pressures perceived by the transducer. This

TABLE 1 Repeatability Summary

Reading Method	Location	Median Standard Deviation (mm)	Maximum Range (mm)	D2S Precision (mm) (1)
Hose 35, Vail Test Site, 4 Repetitions at 43 Positions				
Level Gage	Surface	3.2	31.0	9.1
Rod & Level	Surface	2.2	25.9	6.1
Level Gage	Subgrade	1.0	70.2	2.9
Hose 35, Vail Test Site, Outer 5 Positions Excluded, Each End (2)				
Level Gage	Surface	2.8	22.9	7.9
Rod & Level	Surface	2.2	25.9	6.1
Level Gage	Subgrade	1.0	5.0	2.7

1. Precision estimated by methods described in ASTM Practice C 670, for Preparing Precision Statements for Test Methods for Construction Materials.

2. Outer 5 locations excluded due to variability associated with subgrade hose flexure or highly irregular surface. See discussion on repeatability for comments.

was remedied by protecting both tube ends from the wind without cutting them off from ambient pressure conditions.

Consistency of Readings over Range

Elevation readings were taken over almost the entire range of the pressure transducer during the monitoring program. Some sets of readings ranged over 0.76 m (30 in.) because of the addition of surface material during logging operations and the heaving of surface rock in the center of the roadway. To determine whether the probe measured consistently over its range of about 1.65 m (65 in.), readings were made with the probe housing stationary and the reservoir held at 77 mm (3 in.) increments along a steel rule mounted vertically. An analysis of absolute error (AE) versus elevation difference (ED) indicated the following:

$$AE = -0.0019ED + 0.1917 \qquad r^2 = 0.2090$$

Absolute errors deviated from this best-fit line by up to 3 mm (0.12 in.). For a surface cross section with an overall elevation difference of 0.6 m (24 in.), this would have resulted in a potential error of 6 mm (0.24 in.), within the estimated precision of the instrument.

Rotational Orientation of Pressure Transducer

A question arose as to whether readings would be altered by the orientation of the transducer around its longitudinal axis within the hydraulic hose, particularly since this would be beyond the operator's control. It was not known how precisely the transducer had been mounted within the housing or whether it might have been sensitive to having the air or fluid hose "up." A test was run to evaluate this by taking a series of readings on a level surface and rolling the probe through 45 degrees after each. This test revealed an eccentricity in the probe housing of 1.3 mm (0.05 in.), less than half the estimated precision of the gauge.

EXAMPLE ANALYSIS

In the first phase of the operational test near Raymond, Washington, log trucks made 236 round-trips (empty and loaded passes) on high-pressure tires [600 to 700 kPa (90 to 100 psi)]. The road had 450 mm (18 in.) of surface material (USCS GW, PI 4, less than 1 percent fines, 100 mm top size) over a sandy subgrade (USCS SP, PI 11, 3 percent fines). The in-place CBR of the subgrade was estimated (*8*) as 24 by dynamic cone penetrometer (DCP) tests, which gave a DCP index of 10 to 12. The in-place CBR of the surface was estimated (*9*) as 30 by Clegg hammer readings, which gave a Clegg impact value (CIV) of 18 to 22. The weather was cool with frequent rains. Figure 5 shows several plots of surface and subgrade profiles made during the 5-week period of traffic. Ruts 70 to 150 mm (3 to 6 in.) deep developed in the wheel tracks along with surface heave along the centerline and lateral displacement of the shoulders. Minimal deflections occurred in the subgrade. This pattern of deformation suggests that a bearing capacity failure occurred in the surface material because of the high near-surface stresses.

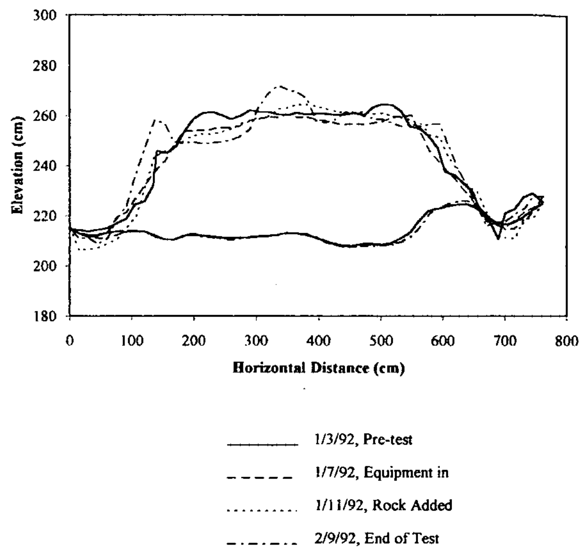


FIGURE 5 Cross-sectional deformations, Hose 4, Raymond, Washington.

Figure 6 shows several sets of data taken at critical intervals at Hose 32 on the upper test road at Vail, Washington. Subgrade CBR was estimated as 10 (DCP 4 to 5), and surface rock with a CBR of 90 (CIV 35 to 40) was applied 230 mm (9 in.) thick. Surface rock was USCS GW, PI 4, less than 1 percent fines, 100 mm top size. Subgrade material was USCS SP, PI 12, 2 percent fines. This cross section was exposed to 447 passes each of empty and loaded log-haul vehicles using tire inflation pressures of 350 to 400 kPa (50 to 60 psi). The weather over the 10-week period of the test was predominantly dry and cool with occasional rain. No significant maintenance was performed on this section of roadway during the test. Modest deformations can be seen developing in both the surface and subgrade as the test progressed.

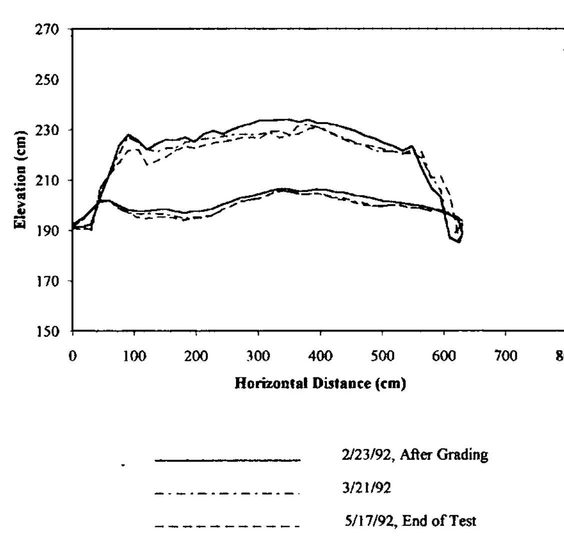


FIGURE 6 Cross-sectional deformations, Hose 32, Vail, Washington.

CONCLUSION

The liquid level gauge developed in this work is a reliable tool for monitoring vertical roadway deformations with a precision of 3 mm (0.1 in.) for subgrade readings and 8 mm (0.3 in.) for surface readings. It appears not to be affected by a wide range of weather and temperature conditions, nor does its accuracy appear to change over its working range. The instrument proved very useful in establishing different trends in aggregate roadway performance under heavy vehicles using different tire inflation pressures.

ACKNOWLEDGMENTS

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