Remote Pavement Performance Monitoring

James K. Cable, D. Y. Lee, F. Wayne Klaiber, and John R. Rohde

The Iowa State University Civil and Construction Engineering Department has initiated a demonstration of pavement instrumentation with the Federal Highway Administration (FHWA) and the Iowa Department of Transportation. The paper outlines the procedures used to establish the project location, select the software and hardware, and complete the installation of more than 120 sensors in a 40-ft segment of I-80. Moisture and density of the base are measured by nuclear means. Temperature of slab and base, strains in the pavement and on the dowels, and deflections of the pavement are monitored. The entire system is triggered by the use of a piezoelectric weigh-in-motion system. Information from the site will provide the research team with a way to monitor the performance of pavement in the field under actual traffic and environmental conditions. The site is unique in that all the electronic sensors will be controlled from a site some 150 miles away and will utilize microcomputers to perform the controls. The problems and results associated with that installation are described.

The reaction of pavement structures to traffic loads and the environment has been studied in many ways in the laboratory. With the exception of the American Association of State Highway Officials (AASHO) Road Test and other previous tests at test tracks, little has been done to test the performance of pavements under field traffic and environmental conditions. Iowa State University and the Iowa Department of Transportation (DOT) are assisting the Federal Highway Administration (FHWA) in demonstrating the use of pavement instrumentation as a way of obtaining these type of data for possible assistance to the states and the Strategic Highway Research Program. A demonstration project entitled "Pavement Instrumentation" (*1*) is designed to demonstrate state-of-the-art equipment and methods in four states and on two types of pavement. Iowa's involvement in the project is providing an opportunity to achieve a better understanding of the performance of portland cement concrete pavements under actual traffic and environmental conditions.

PROJECT GOALS

This project has both short- and long-range goals.

Short-Range

The short-range goals of this demonstration project are

Department of Civil and Construction Engineering, Iowa State University, Ames, Iowa 50011.

1. Installation of instruments in a new pavement during paving operations;
2. Development of a data acquisition system, including hardware and software appropriate to the instruments installed;
3. Installation of a communications link for remote monitoring of the site traffic;
4. Sensor response calibration to the known static and dynamic load situations and ranges; and
5. Installation of the moisture/density instrumentation equipment.

Long-Range

The long-range goals of this demonstration project are to

1. Monitor pavement responses to mixed traffic loads during varying base moisture conditions and varying times of the day;
2. Monitor the changes in density and moisture at the interface of the pavement and the base material;
3. Analyze the response frequency and magnitudes to determine the pavement performance in terms of equivalent axle loads;
4. Compare the rate of pavement loadings to that predicted by the pavement design formulas used in construction;
5. Develop relationships between the observed strains and the measured moisture/density at the pavement/base interface; and
6. Define the drainability of the base material and the performance of the longitudinal subdrains.

PROJECT OBJECTIVES

The study has three primary objectives and several secondary objectives to be achieved through the primary research effort. They are

1. Demonstration of portland cement concrete pavement instrumentation, including the following areas:
   - (a) Instrument placement,
   - (b) Instrument reliability,
   - (c) Hardware and software needs,
   - (d) Instrumentation costs,
   - (e) Potential uses,
   - (f) Evaluation of pavement design and performance, and
   - (g) Assistance in the development of empirical/mechanistic design procedures;

2. Evaluation of dynamic load magnitude and frequency applications to portland cement concrete versus static design loads; and

3. Evaluation of pavement behavior versus various base and subgrade temperature and moisture conditions.

Electronic sensors of the following types were installed at predetermined locations in a 40-ft-long section of I-80 to measure the pavement performance.

1. Concrete strain sensors (locations shown in Figure 1). Measuring 1 in. below the top surface and 1 in. above the bottom surface, sensors were placed longitudinally at midslab in equal transverse spacing increments. Additional sensors were located in an exterior corner on a diagonal. Redundancy of sensor placement was accomplished in two adjacent slabs.

2. Dowel bar strain sensors (locations shown in Figure 2). Measured on selected joint bars under the wheelpaths, centerline, midjoint, and near the slab edges, these sensors were mounted on the bottom of the dowel beneath the proposed saw cut.

3. Temperature sensors (locations shown in Figure 3). Temperature sensors were measured near the top of the pavement, top of the base, and the top of the subgrade. They were rebar mounted near the centerline and 6 in. from pavement edges. Ambient temperature was measured near the control cabinet.

4. Pavement deflection sensors (locations shown in Figure 4 and a cross-sectional view of the gauge housing in Figure 5). Pavement deflection was measured by transducers located in vertical housings in the pavement. Sensors were under wheelpaths and the transverse joint at midslab location. Redundancy was achieved at two consecutive joints and midslab locations.

5. Relative moisture and density sensors. Relative moisture and density were measured by a nuclear density system in pipes at the interface of the pavement and base layers. These elements were measured at three joints and two midslab locations. The sensors were located 6–7 in. below the pavement.

6. Traffic sensors (piezo locations shown in Figures 6 and 7). These sensors measured only single-axle trucks or larger. Axle spacings, vehicle speeds, and axle weights were mea-

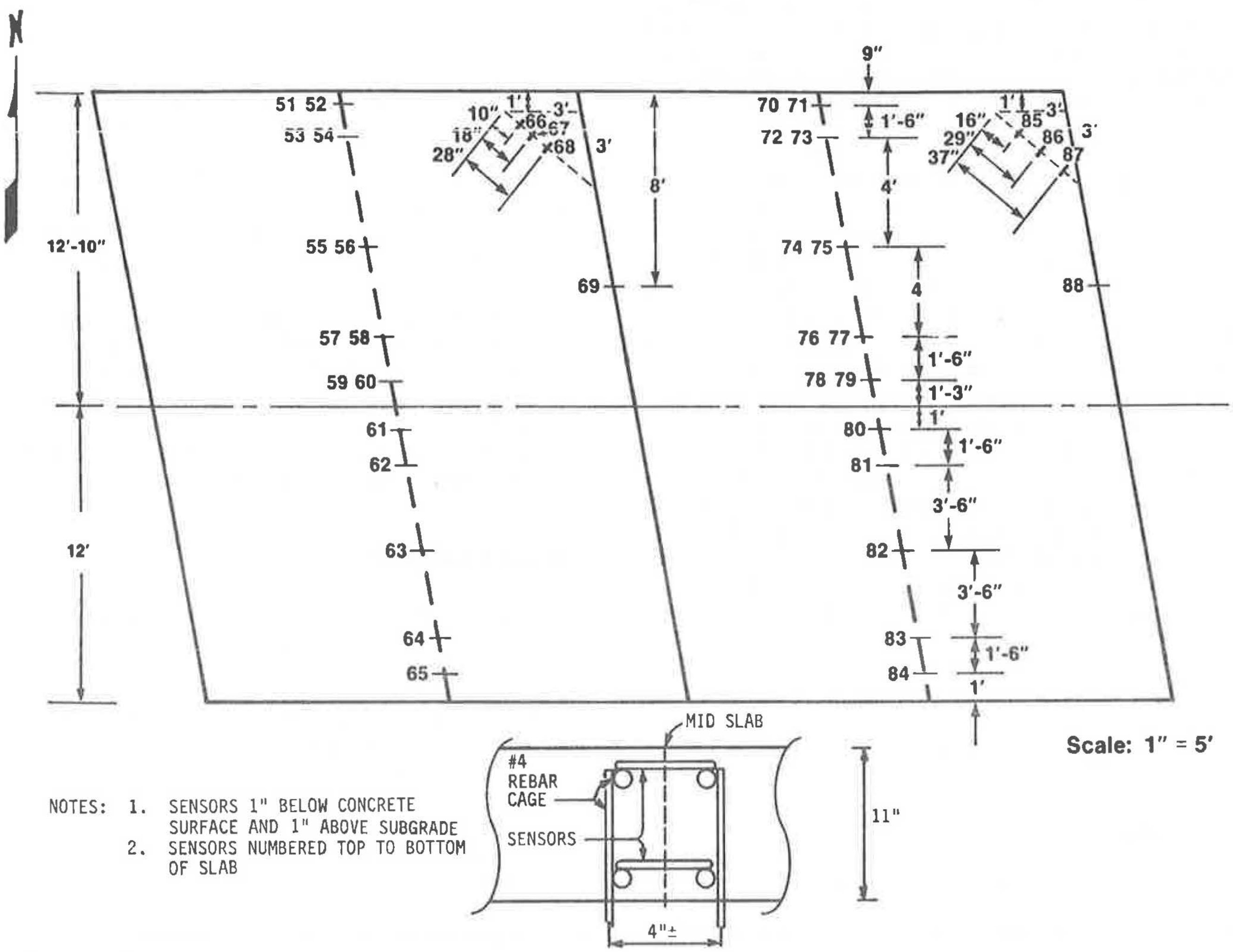

FIGURE 1 Concrete sensor location.

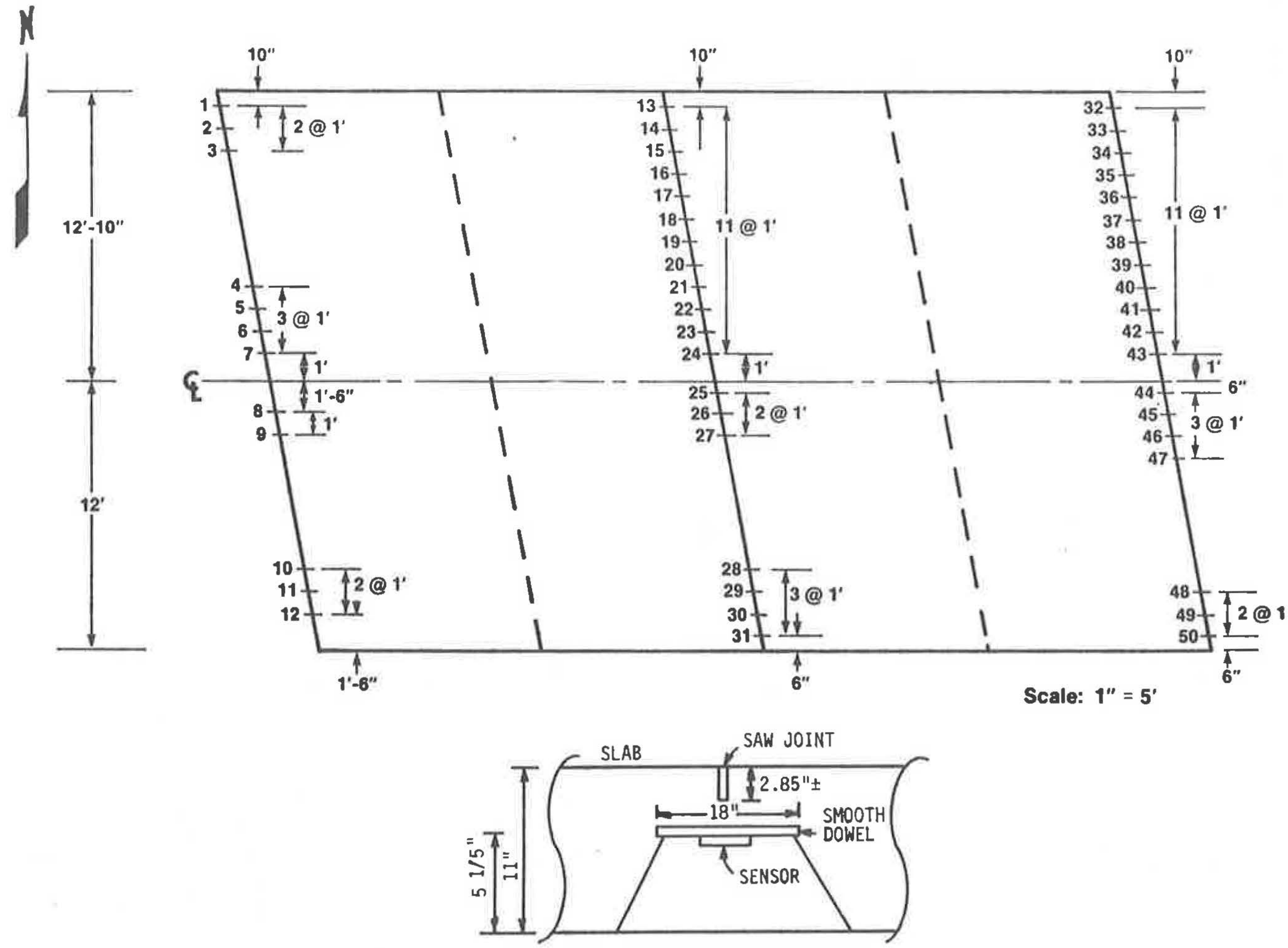

FIGURE 2 Dowel bar sensor location.

sured with piezoelectric cables. Each vehicle was classified by current FHWA classifications. The gross weight of the vehicle and the individual axles were measured with piezo cables.

Initial specifications for the data collection system included the capability of monitoring/scanning each of the gauges or any combination of the gauges in the site at any time at a rate of 1,000 times per second per gauge. Based on cost limitations, a system was selected that provides a rate of 300–400 readings per second per gauge for each of the gauges in two consecutive joints (full pavement width) and the strain gauges in the slab between the joints. The system simultaneously monitors deflection and strain, traffic counting, and classification, temperature, and real time. The data acquisition system is a compromise on account of cost and allows for readings for approximately every 3½ in. of vehicular movement.

The field unit includes a microcomputer, monitor, and storage units with the data collection manager hardware to collect and store data for 1 or more hours of traffic passing the site. The output of the system is in the form of a graphical display and numerical lists of data for each vehicle selected for data collection. It is capable of identifying the strains associated with the loading at any of the individual sensors and of identifying which lane the vehicle is traversing. Data are transmitted via telephone to the central office location in Ames upon demand.

The central office portion of the system serves as the detailed analysis area and includes a microcomputer with plotter and printer to display the analysis results.

Software for data collection and analysis is coming from that provided in the hardware management package subroutines, available spreadsheets, and communications packages. The subroutines to be utilized in the following required programs must be developed by the project staff. They will include:

1. Initiation, completion, and storage of the data from individual vehicles or a series of vehicles in bins with a capacity equal to that of a floppy disk;
2. Conducting a zero reading for each sensor (at predetermined intervals) and collecting temperature data at the same time; and
3. Allowing operator control of sensor selection.

Commercially available communications and spreadsheet software is being used for the majority of data analysis. Other pavement-related software available in pavement design and finite element analysis will be used to verify the pavement design theories.

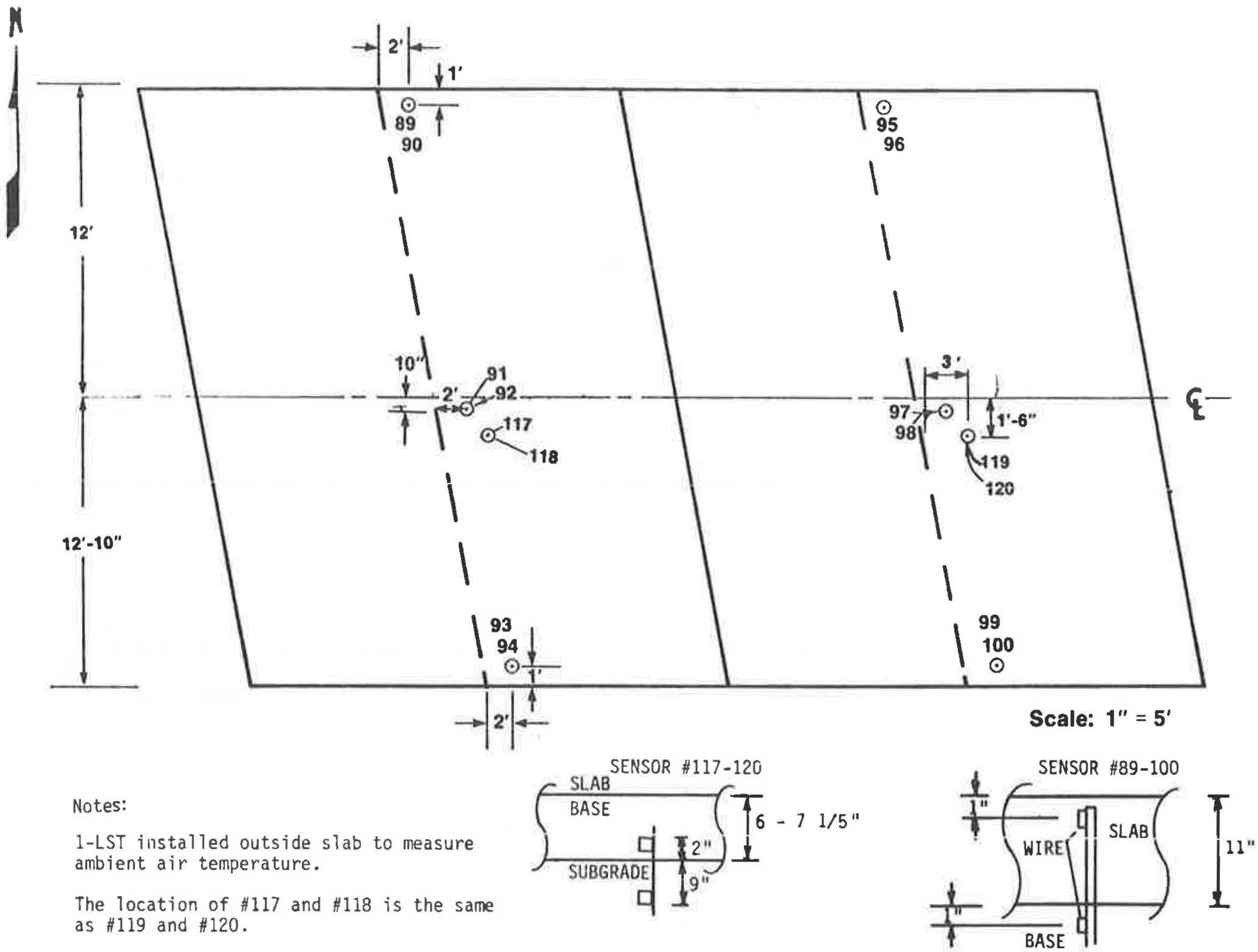

FIGURE 3 Temperature sensor location.

Acquisition equipment can be programmed for data collection rates and times based on the vehicle speed and is triggered by a piezo cable arrangement. Each lane uses a separate piezo cable arrangement. Data will be collected for 3 sec to account for vehicle passage over the test slabs at speeds of 50–90 mph. It also allows for multiples of the 3-sec collection periods for additional vehicles. The piezo cable arrangements are being designed to provide the following accuracies:

- Steering axle—plus or minus 10 percent of static weight on at least 80 percent of the vehicles;
- Other single axles—plus or minus 10 percent of static weight on at least 80 percent of the vehicles;
- Tandem axles—plus or minus 10 percent of static weight on at least 80 percent of the vehicles; and
- Gross weight—plus or minus 10 percent of static weight on at least 80 percent of the vehicles.

Data collected at any given time are limited to the capacity of the floppy disk with 15 percent of the volume left vacant. All information shall be real-time recorded. The field unit will be capable of storing data in increments equal to the noted floppy-disk volume until the total hard disk storage is filled. The unit then waits to be downloaded to the central unit.

The unit will be calibrated with the use of known vehicles and static scales at creep speed, 30 mph, and 55 mph in each lane. Calibration of the piezo cables will use the static scale, and 100 trucks form the traffic stream.

The data collected in the field are to be transferred via modem at 300–1,200 baud using suitable communications software in combination with the appropriate subroutines.

The data collected are to be analyzed to determine the maximum and minimum strains, mean values, areas under the strain curves, and the length and rate of increases and decreases of strain. The zero or null situation will provide for reduction of the data to a standard for analysis. These data will be correlated with the vehicle classification, weight, speed, and location information. They will be used to compare the static and dynamic weights of the vehicles, the weight to strain magnitude, weight to deflection, and frequencies of the strains to the expected pavement damage and what is observed. Use of the moisture/density information will aid in understanding the changes in strain and deflection for given loads over time.

SITE SELECTION

The final site selected for the instrumentation is located in Pottawattamie County in southwestern Iowa in the westbound

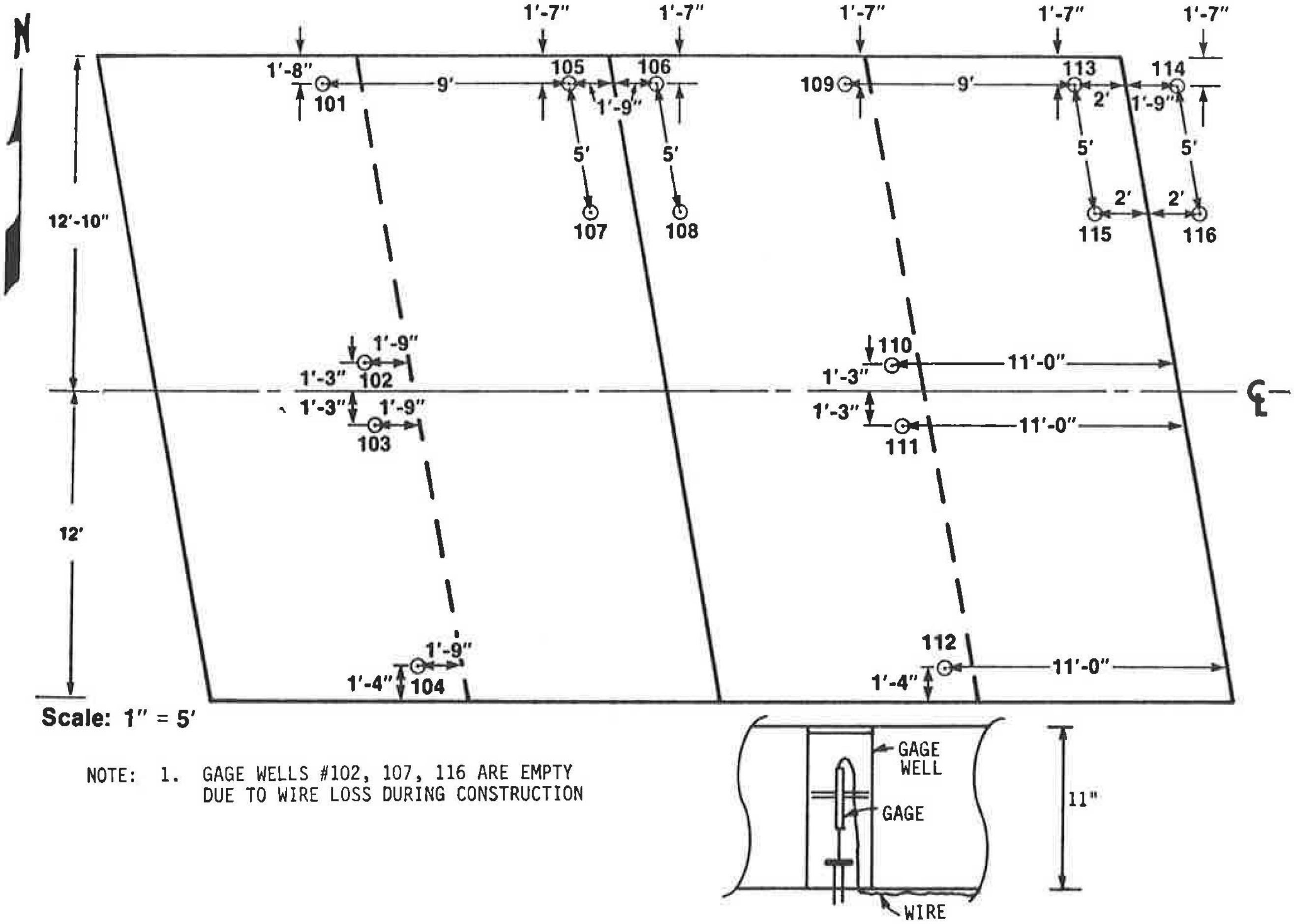

FIGURE 4 Deflection sensor location.

lanes of I-80. The site is part of a 7-mile reconstruction project. The site was selected for the following reasons

1. The pavement was being replaced as part of the reconstruction project. This provided an opportunity for good documentation of the base and pavement characteristics of the reconstruction.
2. The bridge could be used as a weigh-in-motion site for calibrating the sensors in the pavement to known loads. It also could be used for identification of the lateral location and speed of the vehicles entering the test site and crossing the traffic loops. Lane changing by vehicles is reduced on the bridge.
3. This route provided the heavy truck traffic and a mix of truck configurations to test the pavement strain theories adequately.
4. The section is near the low point of a 1,400-ft sag vertical curve, providing a relatively flat grade across the test site. The effects of grade are minimized in the test.
5. The new pavement created a very good chance to obtain a smooth pavement profile at the beginning of the test.
6. A static weight station is located east of the site approximately 15 miles on both the east- and westbound lanes and can be used to check the correlation of weights and strains. A continuous traffic recorder is located in the new pavement approximately 1 mile east of the site in the westbound lanes that can provide ADT counts for pavement wear calculations.

The existing pavement was crushed and returned to the site to be used as a drainable base. The base varied in thickness from 6.5 in. at the median side of the driving surface to 9.5 in. at the outside shoulder. An 11-in.-thick joint reinforced concrete pavement was placed on top of the base. The construction work took place in the summer months of 1986 in stages to meet traffic needs at the various interchanges along the project. Installation was anticipated as early as July but, because of bad weather and other project construction problems, the pavement was placed in this location in September.

The project site is located some 4,000 ft east of both the center of the Minden interchange and all sources of power and telephone. A phone cable and high-voltage power line were buried in a common trench along the north right-of-way line of the interstate highway from a pole at the end of the controlled access in the northeast corner of the Minden interchange. The cable was purchased from the local telephone and power companies and placed using Department of Transportation staff costs.

Aluminum irrigation pipe with a 2-in. inside diameter was installed transversely at each of three joints and two midslabs for nuclear moisture density testing. A common trench

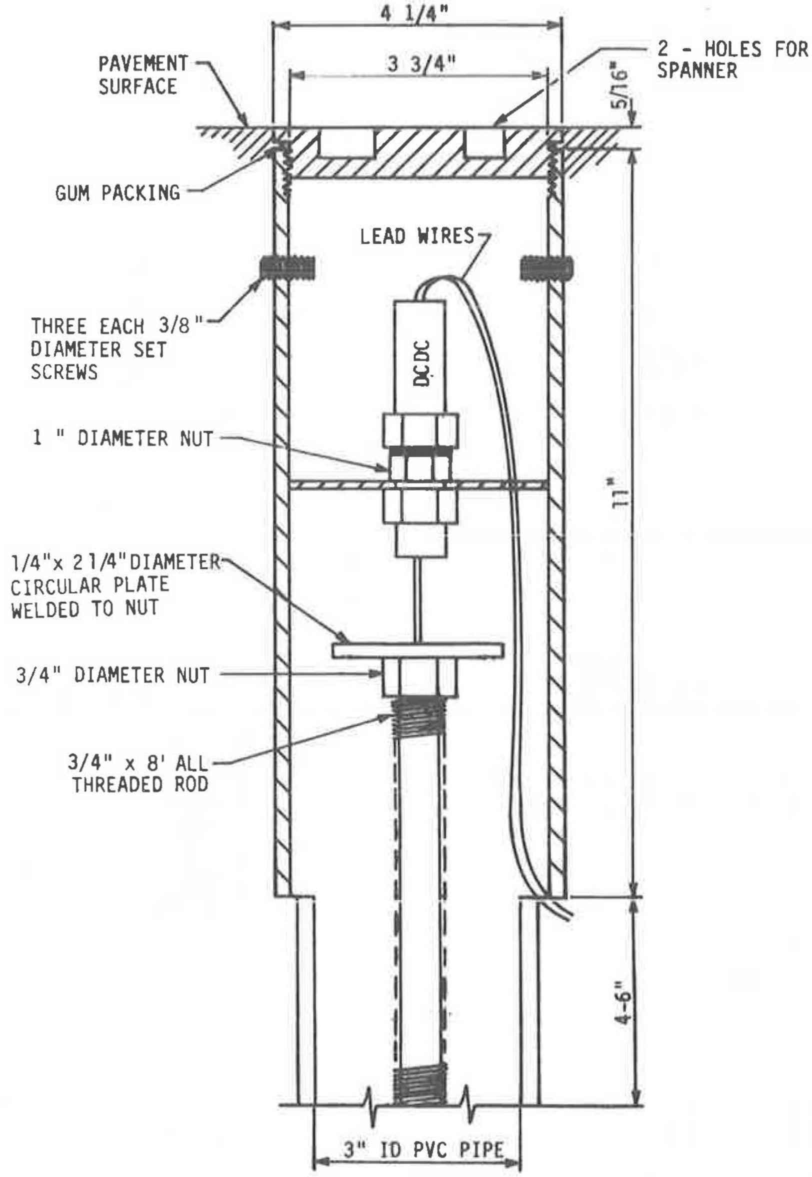

FIGURE 5 Sectional view of the deflection housing.

approximately 6 in. wide was cut longitudinally from the westernmost pavement joint of the test site, easterly on the outside shoulder to the control box site on the wing dike of the Keg Creek Bridge. The control box houses the data collection and storage unit at the field installation.

A soils investigation drill unit was used to drill 5-in.-diameter holes, 5 ft deep, at each of the deflection gauge locations. This was accomplished in the completed base and subgrade prior to the paving operation. A 5-ft section of 3-in.-diameter PVC pipe was inserted in each of the holes. This casing provides protection for the reference rod that was later driven inside the casing. A 1-ft-square section of plywood was used to cover each of the holes during concrete placement. The center of each hole was precisely located by a survey crew for future retrieval purposes. The target plywood section was painted in four colors (red, yellow, green, and blue) and placed in the same color arrangement over each hole. This was done to ensure a way to identify any location changes required in the drilling of the completed concrete to place the housing over the test hole.

INSTRUMENT SELECTION

Costs of purchasing and commercial availability of equipment were the prime considerations in the project. The selection of the concrete and steel strain gauges for this project was based largely on the experience of the ISU Civil Engineering staff. This particular staff has completed similar work on the instrumentation of concrete bridge decks, beams, and railroad subgrades. The particular instruments were selected on the basis of reliability, cost, ease of installation, and durability under field conditions (*2,3,5*). The gauges selected included the following:

- Concrete Strain Measurement: A molded PML-60 gauge

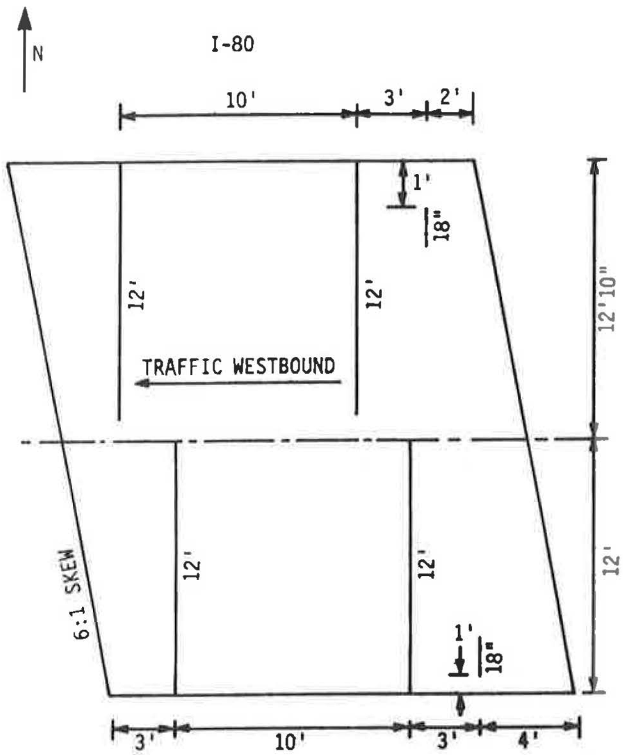

FIGURE 6 Vehicle identification piezo cable configuration.

distributed by the Texas Measurements Inc. Company of College Station, Texas.

- Reinforcing Dowel Strain Measurement: A weldable strain gauge, model LWK-06-W250B-350, made by Micro Measurements Division of Measurements Group.
- Temperature Measurement: A Micro Measurements model WTG-50C grid sensor was used to measure the concrete, air, and base material temperature.
- Deflection Measurement: A Trans-Tek Inc. Displacement Transducer DC-DT series 240-000 was used.
- Moisture and Density Measurement: Troxler density gauge model 1352, with scaler unit and moisture gauge model 3321, with extended probe cables was used for the testing. Special 90- and 100-ft hoses were obtained for the units.

All gauges were prepared for installation in the laboratory at ISU; they were attached to the dowel bar assemblies and tested for continuity and strain registration. The laboratory was used extensively for preparation of the instruments to improve their reliability once installed.

A layout of the site from the construction road plans was established to determine the location of each sensor and the length of wire needed to connect it to the control cabinet. Belden #8723, four-conductor wire in 1,000-ft spools, was used for this purpose because of its insulation and durability features. Some 18,000 ft of wire was required for this project. Each sensor and its connecting wire cable were identified with the cable markers at the control box end. A tag was used to identify the entire unit for placement during installation.

Special housings for the deflection gauges were constructed in the Department of Transportation machine shop from stock materials.

GAUGE INSTALLATION

The goal of the installation was placement of the instruments in the pavement area immediately in front of the paving operation. This required a great deal of coordination with the construction company and the university staff. The fact that the site is some 150 miles from the university added to the coordination problems. Coordination began at the time of highway contract award and continued through the planned July construction date until the installation in September. The entire concrete placement operation was completed at the site in less than an hour with no delay to the contractor.

Several follow-up activities were required to make the site ready for data collection. The first of these were burial of the connecting cables between the site and the control box and construction of the control site. A prefabricated control box was assembled at the site and placed by the department staff. The metal box includes a special electric heater and air conditioner to provide a constant temperature and humidity for the data collection equipment housed in the control box. The box is also insulated, lighted, and equipped with a telephone to provide full field communication and work space. A special transformer and base immediately adjacent to the control box, to step down the 7,000-volt line to the 110/220-volt connections, were required.

The final site work performed prior to opening the road was installation of the deflection gauges using a concrete core drill and the specially built housings.

GAUGE TESTING

On August 10–11, 1987, continuity testing of the instruments was conducted in the field. Completed circuits were found at

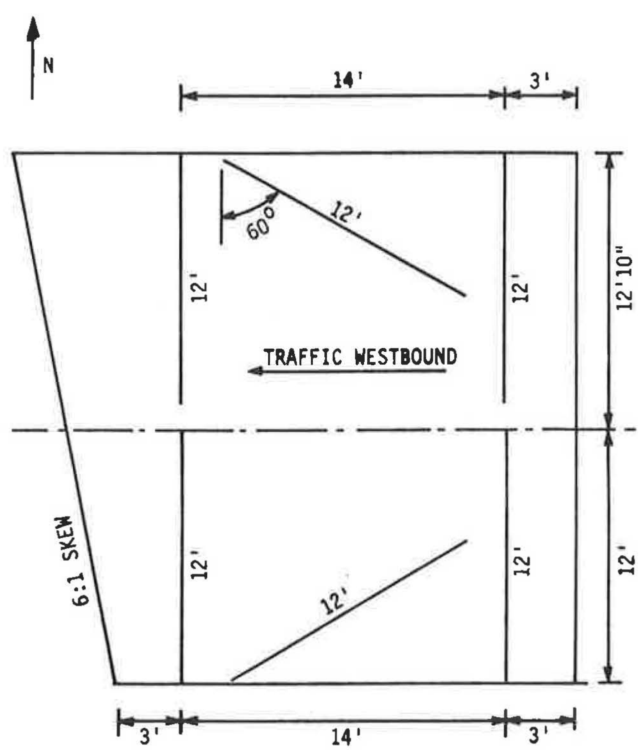

FIGURE 7 Vehicle lateral location piezo cable configuration.

48 of 50 weldable gauges. One gauge provided no circuit, and another showed signs of damage and inconsistent results. Of the 38 concrete strain gauges installed, 3 gave no response and 1 gave intermittent response. All 16 temperature gauges responded positively. Three of the 16 deflection gauges were not installed because of damage to the wiring. Of the remaining 13 gauges, 1 showed signs of fluctuating voltages during testing. This represents a 92.4 percent positive response. This is very good compared with other study results, where a 50 percent failure rate is not uncommon.

EQUIPMENT SELECTION AND PURCHASE

A decision was made in the development of the work plan to provide a form of remote sensing in connection with the project. Equipment was to be selected that would provide on-site collection and analysis of multiple gauge outputs. The results were to be available at the site for calibration and analysis as well as being transmitted over telephone lines to a central Ames location. The original plan called for the field unit to have the ability to scan up to 120 separate gauges at the rate of 1,000 times per second. Compatibility with existing hardware at the Department of Transportation was a consideration, as was the mobility of the equipment to be moved to another site in the future.

Hewlett Packard equipment was selected for the project. The hardware consists of a model 310 series workstation for the central Ames office site and a model 320 series engineering workstation for the field location. The central location microcomputer has a color graphic monitor and associated card, 1 megabyte of RAM, and a 20-megabyte hard disk with the floppy disk. An eight-pen plotter and printer are connected to this unit in a special cabinet for transport between offices. It uses a 2,400-baud modem for communication with the field unit.

The field unit is equipped with a monochrome monitor, 3 megabytes of RAM, and a 40-megabyte hard disk. It is also connected to the central office via the 2,400-baud modem. Each of the units comes with the basic 4.0 operating system.

The heart of the data collection system is a HP 3852A Data Acquisition and Control Unit with two extender units (3853A). Accessories include two 24-channel multiplexers, two 13-bit high-speed voltmeters, a five-channel counter totalizer, data acquisition software routines, a DC power supply, and enough connection devices to monitor forty 120-ohm strain gauges and eighty 350-ohm strain gauges simultaneously.

The equipment was shipped to the Iowa DOT and assembled at the office, rather than at the field location, by the research staff. This proved helpful in assuring delivery and assembly of all parts, as well as aiding staff members' understanding of the operation and development of required software. The units came with the basic operating software and the subroutines to perform the scanning, analysis, and data storage functions.

PROJECT PROBLEMS

As the project developed, problems were noted that can delay an experiment of this type. The distance of more than 150 miles between the office and the site made coordination difficult during installation, calibration, and operation of the remote sensing.

The installation was also delayed some 4 months because of paving construction delays and bad weather. In addition, lack of utilities at the site caused additional time and costs to the project that were not anticipated in the planning phase.

Computer hard disk failures and changes in equipment caused a loss of some 6 months in site installation. Computer software availability and training caused an additional 6 months in preparation for site operation.

The scope and size of the project, which will provide answers to many questions, will also create a similar magnitude of problems in installation and operation. One such problem was that the sensors selected for the project were designed to be relatively inexpensive. They are not designed to last for several years in such a location. Several have failed prior to the collection of any data. This problem reinforces the need to provide redundancy in sensor installation.

RECOMMENDATIONS

Project Planning

Construction of the project presented an evident need for the approach of an interdisciplinary team, including a pavement engineer, a programmer, a research with experience in sensor selection and installation, a computer/communications specialist, and department representatives from the areas of construction, maintenance, and materials.

Site Preparation

Coordination and communication between the project contractor and the research team are a must to assure installation success. These are especially important in

1. Construction scheduling,
2. Storage of construction materials, and
3. Subcontractor and utility activities.

Proper estimation of utility installation and operation costs is also necessary.

Gauge Preparation

Prepare the gauges and lead wiring in the lab, and pretest all gauges prior to field installation.

Gauge Installation

Prepare an installation diagram, and conduct a trial run of the installation at the laboratory. Use an ample amount of trained staff members for the installation.

Data Handling Preparation

Several items of information must be decided in the planning stages of the project to make this portion of the work proceed

smoothly and on time. The project investigators must establish answers to the following questions:

1. What will be measured?
2. How fast will it be measured?
3. What are the limitations of the sensors that the data collection equipment will need to meet?
4. What are the budget limitations on hardware costs?
5. What will the location of data collection and analysis be?
6. What system operation and data analysis software will be used?
7. What software sources are to be used—commercial or in-house?

A literature search also pointed out the strong and weak points of various types of sensors for consideration in obtaining maximum reliability of survival in the concrete situation (*3–5*). The speed of data collection and the number of sensors to be scanned at any one time have a direct bearing on the cost and size of the data collection units. The cost of scanning 120 instruments at the rate of 1,000 times per second per instrument was estimated at between $175,000 and $200,000. By reducing the rate of scan to 300–400 times per second per instrument and scanning some 50–80 instruments at a time, the price was reduced to $60,000.

Delays in the delivery of data collection equipment happened because of the nature of the order. In most cases this is a special order of several parts of subsystems and requires close communication between the investigator, the purchasing agent, and the vendor representative. Cooperation in this case was good, and some equipment had to be returned and replaced owing to incompatibility of parts or changes in the method of handling the data.

The project team chose to use the subroutines provided by the vendor to do some of the data analysis at the field site. In-house programming was used to tie the subroutines together and transmit data to the central office. This work is still under way.

TOTAL SITE COSTS

The following represents a cost estimate of the various parts of the installation as stated in the original proposal.

Item	*Actual/Projected Cost*
Gauges—purchase and installation	$ 58,500
Power and telephone supply to the site	8,000
Monthly service charges for power and phone—2 years at $125 per month	3,000
Consultation travel expense	2,500
Computer hardware	65,500
Software, testing analysis	33,700
Weigh-in-motion materials, equipment, and installation	14,000
Total	$185,200

SUMMARY AND CONCLUSIONS

The instruments have been installed in the pavement during paving operations and exhibit excellent survival rates. The project has the potential to measure deflection and concrete and dowel bar strain at successive joints and to relate this to the loads and the moisture/density changes at the pavement/base interface. It has been shown that arrangements can be made to monitor the information remotely, without the knowledge of the vehicle operator. In the future this will assist the research staff with their ability to monitor vehicle location on the slab, weights, strains, and deflections. It can also be used to calibrate deflection measuring equipment.

The results to date provide information on the costs, problems, and planning steps that should be considered in the establishment of instrumentation sites to answer pavement performance questions. Details of the installation, costs, problems, and conclusions reached during the initial phase of the project are included in FHWA Demonstration Projects Division Report FHWA-EP-88-621-001 (*1*).

Work will continue on calibration of the site to known weights of trucks under both static and dynamic conditions and the collection of data for the next year. Personnel training for computer operation will also continue at both the Iowa Department of Transportation and the university. Additional consideration is being given to a future project to investigate the retrofitting of additional sensors to replace those that have failed to date.

REFERENCES

1. J. K. Cable, J. R. Rohde, D. Y. Lee, and F. W. Klaiber. *Experimental Project No. 621, Pavement Instrumentation*. FHWA-EP-88-621-001, Demonstration Projects Division, FHWA, U.S. Department of Transportation, March 1988.
2. J. T. Christison. In Situ Measurement of Pavement Behavior Under Load. Paper presented at the annual conference of the Roads and Transportation Association of Canada, Sept. 25–29, 1983.
3. B. E. Colley, C. G. Ball, and P. Arriyavat. *Evaluation of Concrete Pavements with Lane Widening, Tied Concrete Shoulders, and Thickened Pavement*. Report prepared for the Minnesota Department of Transportation by the Portland Cement Association Research and Development Construction Technology Laboratories, Skokie, Ill., Sept. 1977.
4. H. Wang. *Comparisons of Solutions for Responses in Jointed Concrete Pavements*. M.S. thesis. Iowa State University, Ames, Sept. 1987.
5. T. D. White. *Instrumentation for Flexible and Rigid Pavements*. Report prepared for the Experimental Application and Evaluation Branch, Demonstration Projects Division, FHWA, U.S. Department of Transportation, June 1985.

Publication of this paper sponsored by Committee on Pavement Monitoring, Evaluation and Data Storage.