APPLICATION OF STRAIN MEASUREMENTS TO SOIL COMPACTION EVALUATION

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The purpose of this study was to investigate the use of soil strain measurements for observing compaction of earth materials in the field. The sensors consisted of disk-shaped coils embedded in the material; the distance between adjacent pairs was determined by inductance coupling. Experiments were conducted on portions of an Interstate highway in New York and on a special test section at the Waterways Experiment Station in Vicksburg, Mississippi. Techniques for sensor installation were developed, possible field applications were demonstrated, and advantages and limitations of the concept for compaction evaluation were determined. The instrumentation system performed satisfactorily in the field construction environment. The sensors survived compaction in crushed slag and gravelly backfill. The measurement of vertical and horizontal strains permitted calculation of percentage of density change. Resolution was about 0.1 percent strain under normal conditions. A recorder detected much smaller changes. Strain measurements were particularly useful for evaluating variation of compaction with depth, compaction changes with each roller pass, secondary compaction as additional layers were added, variability of end results, and difference in capability between compactors.

•METHODS of evaluating field compaction of highway materials have been limited almost entirely to surface density measurements. The devices used include a sand cone, rubber balloon, or nuclear detector, which, in some materials, such as rockfill, lightweight aggregate, and variable till, may be unsatisfactory. In addition, the methods are impractical for use in investigating important factors such as the variation of compaction with depth, the benefit of each successive roller pass, the change that occurs in lower layers during compaction of the surface lift, the relative effectiveness of alternative compactors, and the long-term volume changes in compacted fills associated with consolidation and with moisture and temperature variations. Because compaction is a process of densifying the material by decreasing its volume, volumetric strain is a direct quantitative measure of the amount of compaction. Therefore, a strain sensor embedded in the material is a conceptually feasible way to investigate compaction factors.

The objective of the study reported in this paper was to investigate the feasibility of using newly developed instrumentation (1) and, in the process, to establish techniques for its application in the field. Field experiments were conducted during the summer of 1970 in connection with construction of a portion of Interstate highway in the vicinity of Olean and Jamestown, New York. Those experiments were followed by special compaction tests in January 1971 at the Waterways Experiment Station in Vicksburg, Mississippi. The latter tests provided the opportunity to complete the assessment of the techniques through controlled conditions that were not present during the summer construction operations. A detailed description of this research is given in an earlier report (2).

INSTRUMENTATION SYSTEM

The strain gauge system consists of a pair of embedded sensors and an external instrument package connected by electrical cables. The sensors, each of which is a disk-shaped coil, are placed in the soil in either coaxial alignment (Fig. 1) or coplanar alignment (Fig. 2). They are separated a distance over which the strain is to be averaged. A matrix combining the coaxial and coplanar configurations may also be used (Fig. 3). The coil diameter can be selected to fit the job requirement. To date, diameters ranging from 1 to 14 in. have been tested. In this study, only the 4-in. size was used because sensor spacings in the range of 6 to 12 in. were desired. Durability and low cost were considerations involved in sensor design.

The principle of operation is based on mutual inductance between the coil sensors. A 20-kHz frequency current is established in one of the coils and creates a magnetic field encompassing the second coil in the pair. That induces a current in the second coil, the magnitude of which is directly related to the separation of the sensors.

An important feature of the system is that the sensors are free-floating in the soil to provide minimal interference with the soil movement. The system is electrically designed to operate at any sensor spacing between 1 and 4 times the nominal sensor diameter. The effects of rotational or transverse movements, which cause misalignment, are normally of second order compared to the primary effect of spacing change. The effect of soil moisture and temperature change is negligible, and rarely does soil composition have to be considered. Finally, the effect of different cable lengths is small and can easily be accounted for during calibration. Verification of these characteristics is given in earlier reports (1, 3, 4).

The bridge balance is accomplished on the external instrument package by means of phase and amplitude controls; a meter is used to indicate null. The amplitude digital dial reading corresponds to the sensor spacing. Changes in spacing may be determined by renulling and noting the changes in the amplitude reading. They may also be determined by meter deflection from zero or by voltage output on a recorder connected to the rear panel. When these latter methods are selected, the calibration control is used to adjust the output sensitivity so that it corresponds to a desired amount of strain. The instrument is battery-operated and completely portable, which is a convenience especially desirable in the field.

The method of system calibration is conceptually simple. The sensors are aligned in either the coaxial or coplanar configuration, and amplitude readings are obtained for appropriate sensor spacings. Calibration curves are then drawn relating spacing to amplitude and strain to change in amplitude. A fixture like that shown in Figure 1 for positioning the sensors at known coaxial spacings simplifies and expedites the calibration process.

RESULTS OF FIELD TESTS

The field installation plan depends on the particular application for which the sensors are being used. The procedures are different for compaction with a sheepsfoot roller and for compaction with a smooth-drum roller. The requirements are different for granular backfill and for cohesive embankment material. Finally, a distinction must be made between the large strains during initial compaction and the smaller long-term changes. The experiments conducted in this study were directed toward one or more of these situations in order to establish techniques and assess the suitability of the instrumentation. Examples of the results are described in this paper. Detailed descriptions of the tests and sensor-installation procedures are given in another report (2).

Some of the strain data were used to estimate density changes from compaction. In doing so, the relation used was that the percentage of change in density from the initial state equals the sum of the vertical, longitudinal, and transverse strains, expressed as a percent. If, for example, the horizontal strains (longitudinal and transverse) are small compared to the vertical strain, then the percentage of density change will approximately equal the percentage of vertical strain.

Embankment Compaction

The first example involves a matrix of 9 sensors installed in a rocky till embankment material compacted in 8-in. lifts by a sheepsfoot roller. The sensors were placed 3 each in a coplanar configuration (Figs. 2 and 3) at the top of 3 successive lifts after compaction. Additional lifts were then deposited and compacted. The sensors provided measurement of horizontal strains during primary compaction (compaction of the soil when it is the surface layer), both parallel and perpendicular to the direction of roller travel, and vertical strains through the lifts during secondary compaction (subsequent compaction of a lift during placement and rolling of superimposed lifts).

The results suggested that satisfactory sensor performance can be obtained during secondary strain observation in a variable embankment material, even with a sheepsfoot roller, when the sensors are placed at the top of each compacted lift after the loose surface material is removed. Because the lifts were too thin, no information was obtained in this experiment on the vertical strains during primary compaction. The magnitude and sign of the horizontal strains were quite variable (Fig. 4). Large horizontal strains occurred only during the first few roller passes of primary compaction, if at all; subsequent changes were small. The 3 vertical sets of sensors in each lift showed the same trends for strain although the magnitude varied among them (Fig. 5). In every case, the significant strains were compressive. The observed differences are believed to be a result of the variability of the fill material. Compressive strains were observed to occur in the instrumented layers during secondary compaction of 3 subsequent lifts; thereafter changes were small. The equivalent density change associated with the secondary strains appeared to be as much as 6 $\mathrm{lb/ft^3}$.

Granular Backfill Compaction

In the second example, 21 sensors were installed in coplanar groups of 3 between successive lifts of granular material being placed adjacent to sheet piling (Figs. 6 and 7). The material was deposited by truck, spread in 6-in. layers with a bulldozer, and compacted by self-propelled, smooth-drum vibratory roller. The sensors measured horizontal strains, both parallel and perpendicular to the direction of roller travel, and vertical strains through the lifts. Some 6-in. lifts were not compacted until the next lift was placed, giving the effect of a 12-in. lift spread in two 6-in. sections. This procedure provided information on the strains during primary compaction. In the remaining cases, the strains were recorded only for secondary compaction.

The strain sensors were found to be suitable for application to coarse granular material. The use of a smooth-drum roller permitted simple and accurate sensor placement on the compacted lift surface.

After primary compaction of 6-in. lifts with roller passes on the order of 6 to 8, secondary density changes still occurred during compaction of the next 2 to 6 lifts or 1 to 3 ft of fill (Fig. 8). Increases of as much as 6.5 $\mathrm{lb/ft^3}$ were estimated from the data. Horizontal strains tended to be compressive in the direction of roller travel and extensional in the transverse direction. Usually, these strains did not change significantly after the lift directly on top of the sensors had been compacted. The vertical strains were observed to vary by 50 percent or more within a 1-ft diameter circle. These appear to be real differences resulting from variability of the material, particularly the size and number of the large particles, in the area of the sensors.

Stacking Evaluation

In the third example, a group of 16 sensors and 2 settlement platforms were installed in a till embankment material delivered by truck and spread with a bulldozer (Fig. 9). Compaction was specified in 12-in. lifts with either a sheepsfoot roller or a self-propelled, smooth-drum vibratory roller. The settlement device was of the water overflow type and was connected by plastic tubes to a readout post. The sensors were placed on top of each successive lift after compaction. Thus, only secondary strains were measured. The settlement platforms provided a means of correcting initial rod readings for subsequent sensor settlement in order to compare them with the embankment movements indicated from the strain gauge readings. The sensors were located in 2 separate vertical stacks to provide a replicate measurement for evaluating strains.

As a result of the wide variations in construction procedures, the final strains were quite different among the group of lifts (Fig. 10). However, the strains measured at

Figure 1. Sensors in coaxial configuration for rapid calibration.

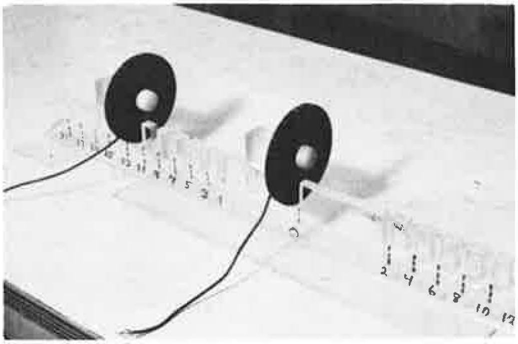


Figure 2. Sensors in coplanar configuration for horizontal strains in embankment.

Figure 3. Sensor layout for embankment test using matrix to obtain vertical and horizontal strains.

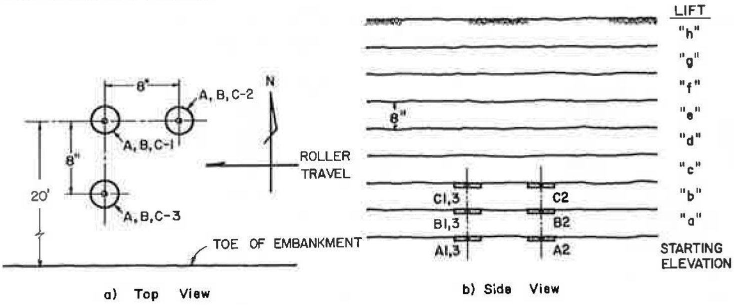


Figure 4. Horizontal strains for embankment compaction.

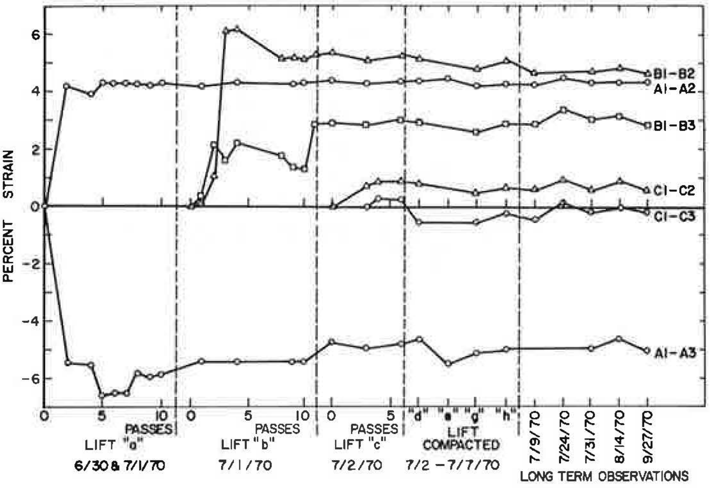


Figure 5. Vertical strains for embankment compaction.

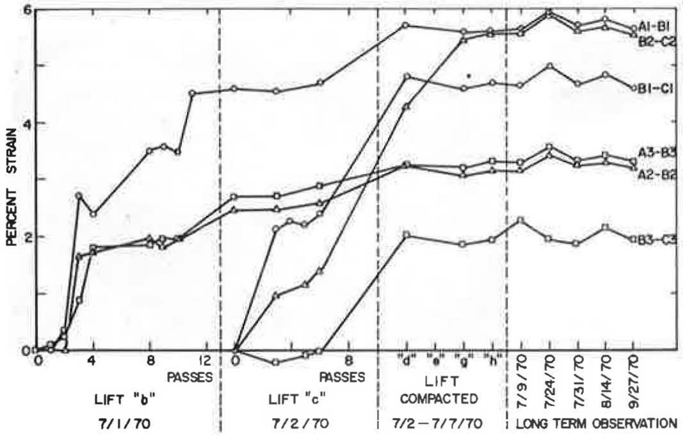
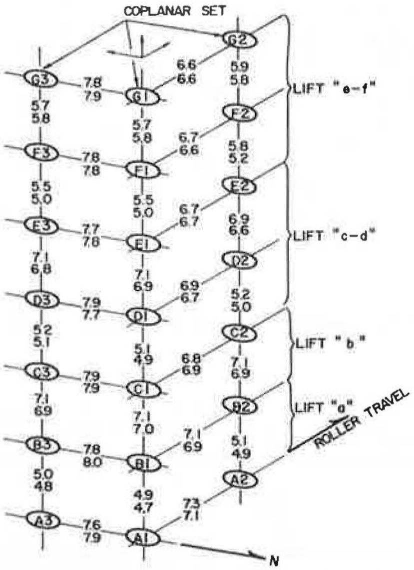


Figure 6. Covered sensors and cables before deposit of loose lift.

Figure 7. Sensor configuration in granular backfill adjacent to sheet piling.



Note: Upper number is spacing after initial placement, and lower one is spacing at end of experiment. Dimensions are in inch.

2 points in the same layer showed general agreement. The differences in replicate measurements may be accounted for by the material variability, although other factors such as placement techniques, also may have contributed to the differences. The largest secondary strain (lift e) occurred because that lift did not receive adequate primary compaction.

The difference in elevation between the lowest and the highest sensors in the fill was measured by summing sensor spacings obtained from the electrical readings. These results were checked with values obtained with a rod and level after adjustments were made for settlement of the lowest sensors. The agreement was within 0.55 to 0.75 percent for 2 instruments, showing that the strain gauge can be used to determine changes over distances greater than the spacing of a single pair of sensors. Agreement between the electrical calculations for each adjacent pair of sensors and the elevation differences was good and within the accuracy of the elevation differences.

Thick-Lift Compaction

The fourth example concerns an experiment performed in a natural gravel fill material in a section of highway embankment. The instrumented test section was formed in this fill by excavating a trench about 4 ft deep and 11 ft wide with a bulldozer. Fourteen sensors were installed in coplanar pairs (Figs. 11 and 12) in the material at successive elevations about 8 in. apart in a single lift having a total height of approximately 56 in. The entire lift was then compacted by a self-propelled, smooth-drum vibratory roller. No compactive effort was applied until all of the sensors had been placed.

The sensors including cables satisfactorily endured the environment imposed by the coarse granular material. The lift thickness determined by summing the coaxial spacings compared well with the rod and level readings.

The sensors were most effective in showing the relative change in compaction with each pass. The strain gauge provided a means of monitoring those changes throughout the entire depth below the surface as rapidly as the roller completes its pass and without disturbing the material (Fig. 13).

The 2 replicate vertical columns of sensors gave similar results (Fig. 14). The differences may be satisfactorily explained by the variation in the granular material properties from point to point in the lift.

The maximum vertical strain occurred at the top of the instrumented section, which was 6 to 14 in. below the surface of the lift (Fig. 14). The minimum vertical strains occurred just below the middepth. Significant strains were produced even at 4 ft below the surface and were believed to have resulted from a saturated moisture condition existing in the bottom portion of the lift and caused by heavy rain prior to compaction. The percentage of density increase caused by compaction as calculated from the vertical and horizontal (transverse) strains was about 18 percent at the top, 7 percent at the midheight, and 10 percent at the bottom of the lift.

Compactor Comparison

The fifth example involved thick-lift compaction of granular material in a trench similar to that in the previous example. In this test, conducted in a covered facility at the Waterways Experiment Station, 2 sets of sensors were used to provide a comparison of operating procedures with a vibratory roller.

Twenty-six sensors were installed in granular material in 2 different stacks, and individual sensors were spaced vertically about 9 in. apart over a total height of approximately 5 ft (Fig. 15). This entire loose lift was then compacted by a self-propelled, smooth-drum vibratory roller. As the roller approached stack A, the vibration frequency was adjusted to give maximum amplitude of drum motion. That condition was held until midway between stacks A and B. At that point, the frequency was changed to 1,800 rpm and held constant until the roller reached the end of the test section.

Nuclear moisture and density readings were made at several depths during lift construction. After compaction, the test section was disassembled carefully to permit checking sensor spacings and to provide the opportunity for final nuclear measurements below the surface.

Figure 8. Vertical strains during backfill compaction.

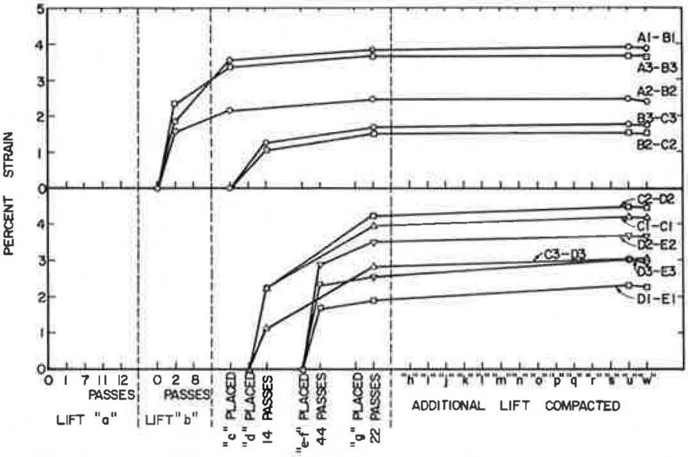


Figure 9. Sensors and remote readout settlement platform in position during checking of level of plane of sensors.

Figure 10. Variation of final strain with depth.

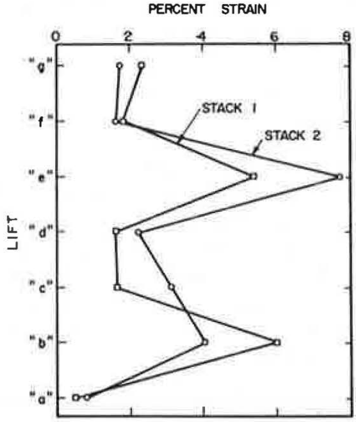


Figure 11. Sensor installation in trench.

Figure 12. Thick-lift compaction sensor array.

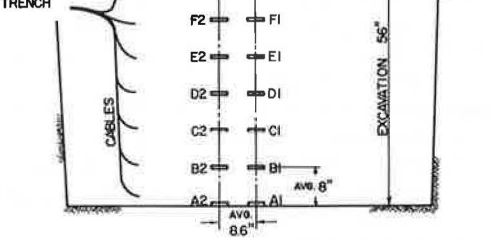


Figure 13. Vertical strain with number of roller passes.

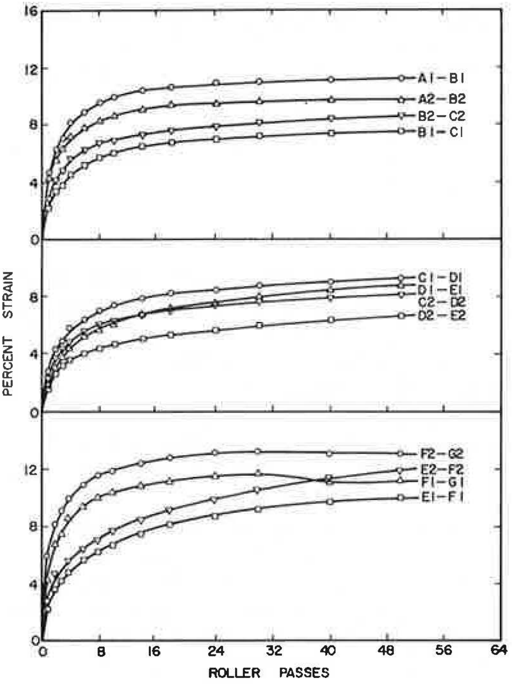


Figure 14. Vertical strain variation with depth after compaction.

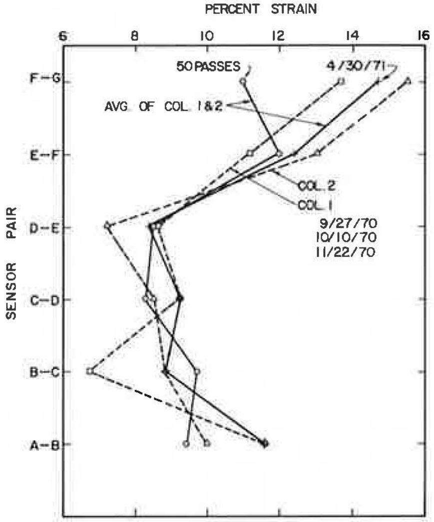


Figure 15. Layout of test section.

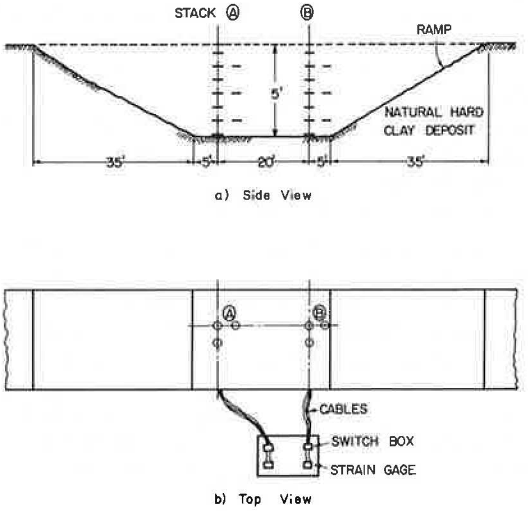
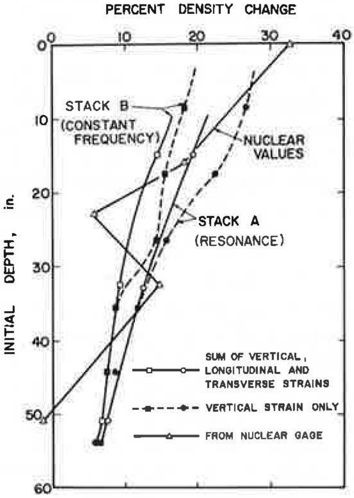


Figure 16. Variation in percentage of density change with depth.



The stack compacted by resonance-seeking procedures experienced significantly greater strains in the top 2.5 ft of the layer than the one compacted by a fixed vibration frequency. However, the differences were very small at the bottom where little compaction was accomplished in either case. Approximate agreement was obtained for percentage of density change computed by the nuclear and strain methods. The discrepancies are attributed to the large variability in density readings, particularly those obtained in the loose soil state (Fig. 16).

The use of switch boxes and 2 instruments made it possible to take the 23 readings after each roller pass in fewer than 5 min. The nuclear instrument was much slower and could only be used on the surface during compaction.

SUMMARY AND CONCLUSIONS

The primary purpose of this study was to evaluate the usefulness of the soil strain gauge system for measuring compaction in the field. The advantages and limitations were sought, and proper techniques for the successful applications were determined.

The wide range of field situations considered in pursuing this objective included materials ranging from unclassified embankment fill to natural gravels and slag, smooth-drum vibratory rollers and sheepsfoot rollers, loose-lift depths from 6 to 60 in., as many as 50 roller passes, a variety of methods of sensor installation, and strains from both primary and secondary compaction with monitoring continued during 9 months in some cases.

The series of field experiments provided not only information on strain gauge performance but also interesting new information on field compaction. Included is the observation that, for normal 6- to 12-in. loose lifts receiving 3 to 6 roller passes, significant additional density increases may occur during secondary compaction, that is, as a result of compaction of succeeding lifts placed on top of the initial lift.

The following conclusions regarding general performance of the instrumentation system are indicated:

1. The sensors may be easily installed with a high probability of successful performance;
2. Meaningful results can be obtained in crushed slag, coarse gravel, and variable till, which are inherently difficult to measure;
3. Independent checks using direct-spacing measurements confirmed the reliability of the electrical readings;
4. For the coaxial configuration, adverse effects due to sensor misalignment, offset, and rotation were shown to be unimportant in almost all cases;
5. The small coplanar strains indicating horizontal changes showed variable trends that could have been a result of offset and rotation effects, but it is equally probable that these trends indicate actual compaction effects; and
6. The precision of long-term readings was on the order of 0.1 percent strain.

A variety of sensor installation techniques were evaluated, and the basic concepts have been summarized in another report (2). The appropriate methods depend on the specific application and the degree of control over the construction operation.

The percentage of vertical strain was shown to be representative of the percentage of density change because the horizontal strains were usually small by comparison. In some cases, a more accurate estimate of density change is obtained if the 3 orthogonal strains (vertical, transverse, longitudinal) are summed. The density change is sufficient information on compaction for many applications. If density is known at any stage of compaction, say initially, then all of the strain readings can be converted to density rather than just to density change.

Based on data from one of the experiments, the error in percentage of density change calculated from the nuclear measurements was 3 times the error in percentage of strain change. Thus, the strain sensors were better able to detect changes in compaction between test sections. However, the difference is even greater if changes between passes at a given point are desired. The strain sensors can readily detect changes of 0.1 percent strain, which corresponds to about 0.1 lb/ft^3 density change, or a factor of 10 smaller than the density methods can be expected to detect.

Examples of application to compaction problems, which seem feasible based on experience in this test program, are as follows:

1. Determine change in compaction with additional roller passes to establish optimum roller efficiency in a particular soil condition;
2. Determine variation of compaction with depth to establish best lift thickness;
3. Determine the effect of compactor parameters such as speed, weight, and tire pressure on amount of compaction and compare the results for a given roller in several types of material;
4. Evaluate adequacy of compaction by comparing change during the application of a proof roller;
5. Provide data on amount of secondary compaction to evaluate the desirability of reduction in the number of passes or applied effort during primary compaction;
6. Monitor changes after compaction to provide an indication of potential instability of the fill;
7. Establish satisfactory compaction procedures for use with materials in which density measurements are not reliable;
8. Determine settlement distribution within a compacted fill by means of a vertical stack of sensors;
9. Evaluate local volume changes of compacted fills caused by changes in moisture and temperature;
10. Observe lateral confinement change due to movements of adjacent structures such as retaining walls and culverts; and
11. Document variability of compaction.

There are also limitations to the use of the strain gauge in compaction studies.

1. In normal field situations, the changes in the top inch or so of material immediately below the compacting element of the roller cannot be realiably measured. That zone is hard to predict for a sheepsfoot roller, and therefore the method may not be feasible for evaluating primary compaction with such rollers.
2. Accurate prediction of density changes may require the determination of 3 strain components if comparison of vertical strains is not sufficient. If the types of compactors are quite different, then all 3 strains may also be needed to ensure proper interpretation.
3. Once sensors are installed, the measurement location is fixed. Information on primary compaction cannot be obtained at other locations after compaction.
4. Dynamic strain measurements during roller passage cannot be obtained closer than 2 to 4 sensor diameters from a part of the roller that influences the magnetic field. For steel-wheeled rollers, this means 8 to 16 in. below the surface with the 4-in. diameter sensors.

The instrumentation system used in this study has evolved from 6 years of research and development, and its feasibility in the field has been demonstrated by the results of the study. Earlier studies demonstrated usefulness in the laboratory. The method is ready for application to appropriate problems. The primary need at this time is the accumulation of experience, and that can only come from use.

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