Pavement Deflections Using Photogrammetric Techniques

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During the past eighteen months, research has been conducted at the Ohio State University on use of photogrammetric techniques in measuring pavement surface deflections under dynamic loading. Although the work has been restricted to surface measurements, base and subgrade movement can also be determined by similar methods.

Control measurements were obtained with deflection bridges using conventional extensometers, with a Benkelman beam device, and with standard electronic techniques (LVDT). Each of these methods for deflection measurements has its disadvantages, the most serious being the inability to get near or under the moving vehicle or the time and expense to obtain an individual reading.

Photogrammetric methods permit deflection readings everywhere except beneath the tire itself. Many points can be studied in a single photograph, and deflection "contours" can be drawn. The major disadvantage is in the accuracy of the measurements. The report covers numerous cases where the accuracy obtained is within 0.005 in. of the deflection measured by conventional methods.

This is a progress report as there are still numerous areas of study to be considered in order to improve the accuracy, to reduce computation time, and to develop equipment and field techniques.

• A CRITICAL NEED in the field of highway pavement design is a realistic approach to the evaluation of the load-carrying abilities of a given stretch of pavement. The problem is frequently encountered as a result of requests for the issuing of overload permits, load restrictions during the period of spring breakup, and general considerations of load limitations.

For many years, frequently changed empirical design relationships have been necessary. As a result, pavements today have varying degrees of permanence for both legal and overweight vehicles. Some of the older pavements should not be expected to withstand as many repetitions of a given axle load as the newer ones (completely excluding the fatigue factor). The premise is that newer pavements are being constructed with greater thickness, higher quality surfacings, and more consistent use of subbases, even though legal load limits have not changed.

If it were possible to evaluate systematically all of the pavements in a state or Federal system, a more objective answer could be given to questions concerning load limitations. However, the absence of a generally accepted, rational method of design precludes such evaluations. One of the reasons for the inadequacies of current formulae might be that continuous observations and measurements of pavement performance have not been economically feasible for most research groups, although much could be learned from such an evaluation.

The development of a method for evaluating existing pavements should have some advantage over a direct research program in pavement design, principally because the interaction between the soil subgrade and the pavement structure need not be predicted from theoretical or laboratory considerations. However, a theoretical approach requires sweeping assumptions on soil and pavement strength characteristics (particularly those related to repetitional, dynamic loadings) for predicting soil-pavement interaction. For evaluating existing pavements, the soil strength characteristics may be important only in the manner in which they vary from time to time, because the effect of the soil must be reflected in the pavement surface behavior. Of course, differentiation must be made between the influences of soil and those of the pavement proper, at some time in the analysis.

Such an approach is not an alternate to large-scale test roads. The facilities of the local area must be studied in detail, if the results of major test roads are to be of value in other areas of the country. The deflection under dynamic as well as static loading should be considered in the evaluation of existing pavements. The results from the WASHO Test Road (*1*), as well as work reported by F. N. Hveem (*2*) and others (*3, 4, 5*), indicate that for the deflection, the vertical magnitude, the number of load repetitions, the areal extent, and the degree of curvature of the pavement surface influence pavement performance.

Currently available methods for measuring these dynamic effects include various types of arrangements for using standard extensometers (*6, 7, 8*), the Benkleman Beam developed at the WASHO test site (*1*), and electronic techniques such as, LVDT and linear potentiometers (*1, 9*). Each of these methods has advantages and disadvantages for dynamic conditions. The most serious difficulty with the Benkleman Beam is its inability to measure effects of speeds in excess of 5 mph, and the requirement that the load does not produce pavement deflections at a distance as limiting as 8 ft from the wheel. The principal disadvantages to the use of electronic units are the expensive field setup, the electrical problems during rainy periods, the unknown effect of a sizeable hole in the pavement directly beneath the tire, and the uncertainties as to the necessary penetration depth for anchorage.

The possibilities of using photogrammetric techniques as an adjunct to studies of pavement performance were first explored at Ohio State University in the fall of 1954. Since that time, research has been practically continuous under the sponsorship of grant-in-aid research and under the auspices of the Engineering Experiment Station. The values of such procedures appeared to be in the simplicity of field operations for dynamic loads, although there was concern as to the degree of accuracy that could be achieved.

In order to avoid confusion as to the proposed use of photogrammetry in pavement deflection studies, one fact should be emphasized. The method is not to be considered as one which excludes all other techniques. The advantages and disadvantages listed in a subsequent section will indicate under what conditions photogrammetry appears feasible. All of the conventional methods have been used at Ohio State and will be used in the future if conditions require. This report covers the development of methodology and is not pure pavement deflection research.

REVIEW OF PHOTOGRAMMETRIC PRINCIPLES

The Committee on Nomenclature of the American Society of Photogrammetry describes protogrammetry as "the science or art of obtaining reliable measurements by means of photographs" (*10*). Terrestrial and aerial photogrammetry are differentiated on the basis of the location of the camera — the former indicating ground locations, and the latter any air-borne vehicle. Stereophotogrammetry consists of measurements made with overlapping pairs of photographs, viewed with a stereoscopic viewing device so as to produce three-dimensional effect. Horizontal photogrammetry is of the terrestrial type for which the optical axis of the camera is horizontal.

The science of optics contributes other

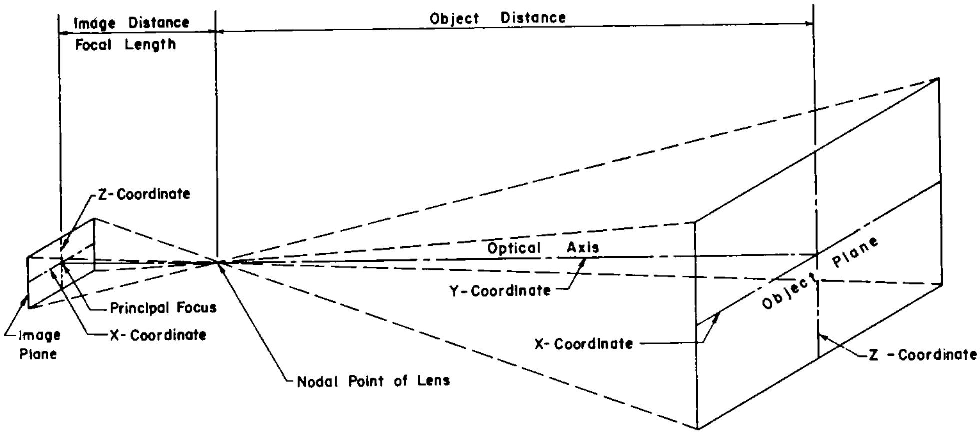

Figure 1. Nomenclature for photogrammetric measurements of pavement deflection.

important fundamentals. The optical axis is defined as a straight line connecting the centers of curvature of the two surfaces of a lens; the principal focus is the point on the optical axis to which the lens converges plane waves. The front and rear nodal points are located on the optical axis, and are the points toward which the incident and the emergent rays tend to converge if not refracted. The following approximation based on a fundamental equation of optics is important:

$$\frac{1}{0} + \frac{1}{I} = \frac{1}{F} \qquad (1)$$

in which

I = the image distance or the distance from the image plane (film or plate) to the rear nodal point measured along the optical axis;

0 = the object distance or the distance from the object to the front nodal point measured along the optical axis; and

F = the focal length of the lens, or the distance from the rear nodal point to the principal focus, measured along the optical axis.

For applications involving relatively large object distances as compared to image distances, Eq. 1 reduces to the following approximation:

$$F = I \qquad (2)$$

In order to determine the scale of the photograph, the following expressions can be used:

$$S = \frac{I}{0} = \frac{F}{0} \qquad (3)$$

in which

S = the scale factor.

The following expression for the scale factor can be used if an object line lies in a plane that is parallel to the image plane:

$$S = \frac{L_i}{L_o} \qquad (4)$$

in which

L_i = length of the line on the photograph and

L_o = true length of the line.

The location of a point in space is frequently defined in photogrammetry on a three-dimensional system of rectangular coordinates. The x and y coordinates lie in a plane that is tangent to the surface of the earth, with the z dimension perpendicular to the earth's surface. The origin is commonly chosen at the front nodal point. For example, the z dimension is the camera elevation (in both terrestrial and aerial photographs), whereas the distance from the camera to the object is the y dimension (in terrestrial photogrammetry).

The dimensions on a photograph are on the same coordinate system except the origin is at the rear nodal point. It is common procedure to superimpose the two coordinates. For ease in reference, a prime mark is placed on the photograph coordinate. For example, in terrestrial photogrammetry, z would represent the ground evaluation coordinate, while z' would represent the same dimension to the scale of the photograph(terrestrial). To simplify the measurement of dimensions on a photograph, film or plates designed for photogrammetric purposes have fiducial marks at the center of the top, the bottom and both edges so that the coordinate system is established with reference to the optical axis.

For photogrammetric analyses, due cognizance must be taken of the errors that develop. Some of the errors involve the human element. Others are related to unavoidable characteristics such as movement of the camera or inconsistent alignment of the film plane and the optical axis. To obtain accuracies of the order normally desired, an analysis of the errors must be completed, and an adjustment made in the measurements. These corrections are normally applied to the ground, rather than to the photographic data.

The error analysis is divided into consideration of inner orientation and outer orientation. The former is related to the camera and its construction; the latter applies to the position of the camera with reference to the object (relative position of the object and image coordinate systems).

For inner orientation, lens distortion and non-perpendicularity between the optical axis and the plate directly influence the dimensions of the photograph. Where two cameras are used, or two photographs are taken with the same camera, differences in orientation of the optical axis and the plane of the negative are also a problem. The computations required for true dimensions are based upon the focal length, which can be a source of error in inner orientation.

The errors of outer orientation can produce constant or linear errors in the photograph dimensions in the plane of any of the three coordinates because of camera or object movement. Furthermore, non-linear errors can be produced by rotations of the camera about any of the three coordinate axes.

PREVIOUS INVESTIGATION

Although several different photogrammetric techniques (*11, 12*) have been used for measuring pavement deflection, each consists basically of taking one photograph of the pavement with no load followed by a second photograph with the load in place. A comparison of the pavement surface elevations as measured from the two photographs produce the deflection results. Specific points on the roadway are examined through the use of "targets" placed on the pavement before either photo is taken. Both static and dynamic loads have been considered. All of the tests utilized standard control measurements to check the accuracy obtained.

Turpin's Studies

The original work at Ohio State University was conducted by Turpin (*11*). Planning for the studies was started in September 1954, and the field work was accomplished in June and July 1955. The targets consisted of ¼-in. steel balls, placed on top of "surveyors tacks" driven into the pavement. The target was, in effect, a highlight on the surface of the sphere. All of the tests were conducted in late afternoon in a well-shaded location with the aid of a flash attachment. A 4 x 5 Speed Graphic camera with a 135-mm lens was used.

One of the principal contributions of this work is the basic error analysis. Assuming that the optical axis in horizontal and that the errors are quite small, the outer orientation errors that affect pavement deflection were expressed by Turpin as follows:

$$dZ = dZ_o + \frac{z'}{f}\, dY_o + \frac{x'Y}{f} dk + \frac{x'z'\,Y}{f^2}$$

$$d\phi + Y\left(1 + \frac{z'^2}{f^2}\right)dw \qquad (5)$$

where

dZ = error in pavement deflection measurement due to a small change in each of the elements of outer orientation of the camera;
dZ_o = change in height of the camera;
dY_o = change in position of the camera along the optical axis;
dk = small rotation of the camera about the optical axis;
$d\phi$ = small rotation of the camera about the vertical axis;
dw = small rotation of the camera about the horizontal axis;
f = focal length of the camera;
x' = horizontal coordinate of points in the plane of the negative;
z' = vertical coordinate of points in the plane of the negative; and
Y = the distance, measured along the optical axis from the plane of the objective to the front nodal point.

Turpin made additional simplifications in his particular case. In Eq. 5, at least five points of known deflection are required for the solution of the elements of outer orientation.

For inner orientation, lens distortion was insignificant for pavement deflection accuracies of the order of 0.01 in. Errors resulting from focal length inaccuracies were also negligible. With the camera, it was probable that the film would be tilted with respect to the optical axis, and these errors analyses were combined with those for camera rotation for outer orientation.

Measurements on the photograph were accomplished by monocular and stereoscopic methods. A measuring engine, with a theoretical accuracy of .001 mm, was used for the former technique, and the x' and z' coordinates were measured on the photographs. The scale was determined by field measurements of the object distances and by comparison of true lengths with image lengths (Eq. 4).

For the stereoscopic approach, photographs picturing "loaded" and "unloaded" conditions were observed under a stereoscope. The principle of these measurements is the same as for other stereo applications. If the two photographs are identical because no deflection occurred, no stereoscopic effect is produced. However, if some of the points have moved, a trained observer will receive a sense of depth. With a measuring instrument (Turpin used a parallax bar) the depth change can be obtained. The accuracy of the approach is subject to the stereovision ability of the observer. However, because of the small values concerned, the stereo method has an advantage in that "differences" rather than actual point locations are obtained.

Despite the relatively inadequate equipment with which Turpin worked, his results were quite satisfactory. Only static loading was considered.

Briggs' Work

During the period June 1955 to August 1956, Briggs attempted to expand upon Turpin's work (*12*).

To circumvent the inherent disadvantages of using steel balls, Briggs selected overlapping strips of plastic tape for his targets. The major reason for the change was the ability to make deflection readings under any natural lighting conditions.

A Wild Stereo camera was used in order to eliminate the field measurements required for determining the scale and to minimize errors of inner orientation. This type of stereo camera consists of two identical cameras mounted rigidly together so that the camera axes are 400 mm apart. The focal lengths are 90 mm, and glass plates 6.5 x 9.0 cm are used.

The stereo effect produced by the two cameras was utilized to compute the scale factor of the photographs, using the following equation:

$$S = \frac{Y}{f} = \frac{b}{x' - x''} \qquad (6)$$

in which

S = scale factor;
Y = distance from the rear nodal point to the plane of the object measured along the optical axis;
f = focal length;
b = horizontal distance between the optical axes of the two cameras;
x' = x-coordinate of a point on one photograph; and
x'' = x-coordinate of the same point on the second photograph.

Briggs used the reciprocal of the normal scale factor (Eq. 3 and 4).

The actual deflection values were obtained by the same method that Turpin used. Error analyses were attempted using Eq. 5. However, problems inherent to the targets and failure to obtain a satisfactory "spread" of control points prevented the development of reliable corrections. Briggs used a system of "error contours" for correcting the data obtained by monocular methods. Figure 2 shows the targets used by Briggs.

Briggs was also responsible for the conduct of a brief series of tests to check the almost unbelievable theoretical accuracy of the Gaertner Measuring Engine at the Perkins Observatory of Ohio State and Ohio Wesleyan Universities. Figure 3 shows the engine and Figure 4 the result of this work. The plates were placed in the engine, and 90 measurements to a point were made. A frequency distribution of the readings was plotted (Figure 4), and the readings approximate a normal distribution as nearly as could be expected. Assuming the distribution was normal, the mean was estimated as 62.9369 mm and the standard deviation as ± 0.0013 mm (1.3 microns). A 90 percent confidence interval on the mean was also computed as ± 0.0002 mm (0.2μ). A normal distribution with the computed standard deviation and mean is shown in Figure 4, and these data tend

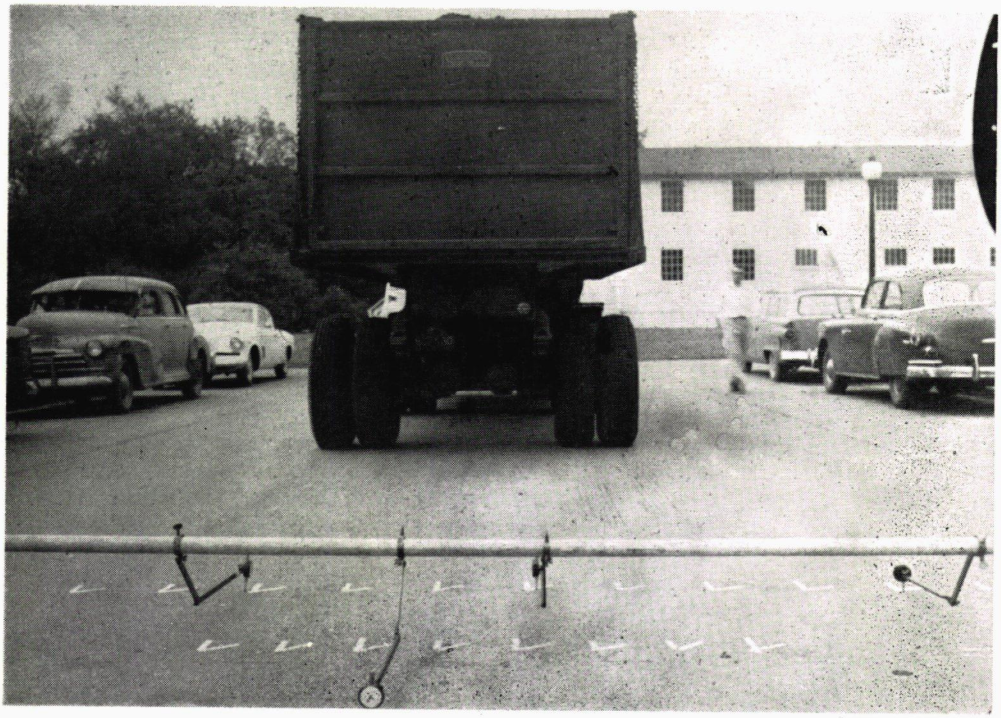

Figure 2. Targets and control device used by Briggs.

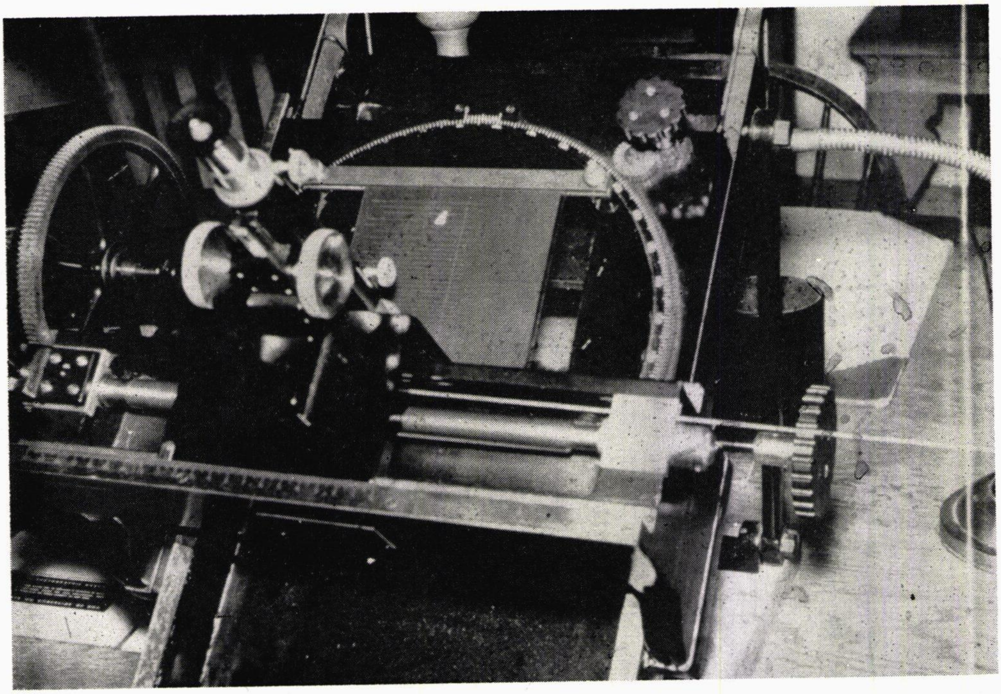

Figure 3. Gaertner measuring engine.

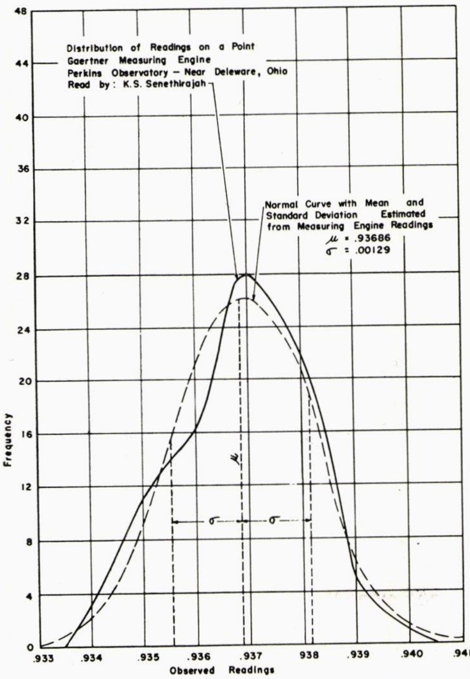

Figure 4. Evaluation of the accuracy of the Gaertner measuring engine.

to justify the assumption that the readings are normally distributed.

The results of Briggs' work are included in Figure 5. Briggs attributed most of the inaccuracies to the inadequacy of the targets and to the camera. Sharp points were not defined on the targets, causing a failure to point to exactly the same spot. As for camera error, the combination of a short focal length and a small plate size resulted in too large a scale factor.

RECENT DEVELOPMENTS

The most recent series of tests was started in October and concluded in December 1956. On the basis of the earlier studies, a review of target requirements and a search for a more adequate camera were considered essential. The added calculations required for determining the scale factor by the stereocamera approach were also eliminated as being less practical than measuring distances from camera to the target grid system, or by comparing ground and photograph dis-

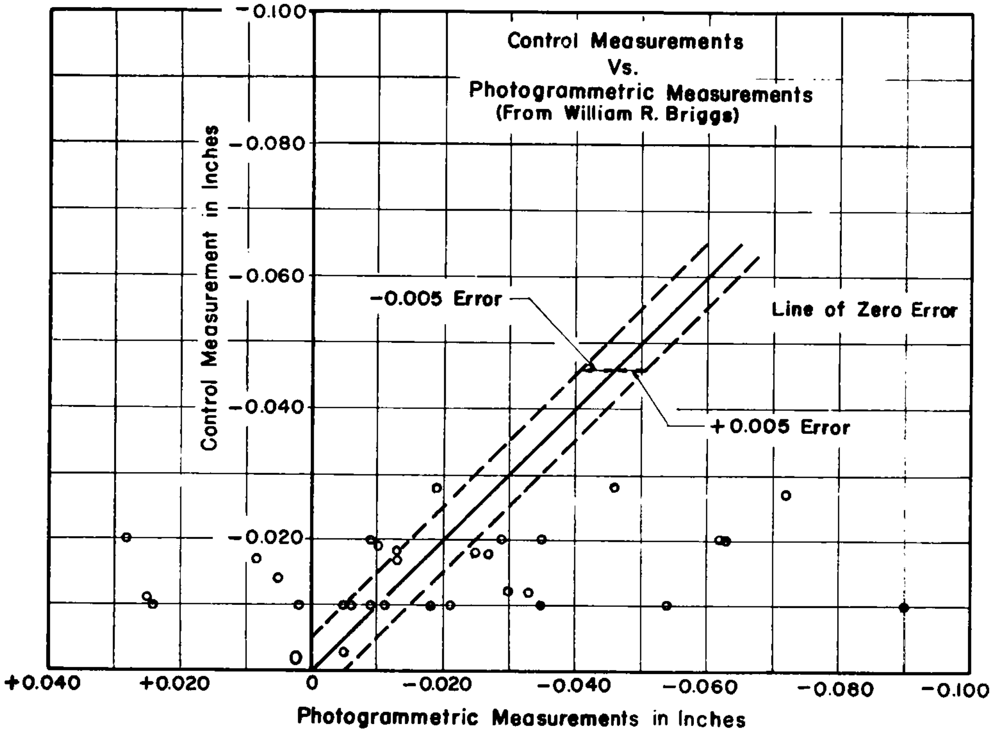

Figure 5. Evaluation of Briggs' results.

tances. A series of tests designed and conducted by K. S. Senathirajah led to the development of a new target. By placing two contrasting tapes in the same plane, the shadow problem encountered with overlapping strips of tape was eliminated. Individual targets were placed at convenient intervals on a strip of pressure-sensitive tape which has adhesive on both sides. After satisfactory preliminary trials with the new targets, pavement deflection studies were interrupted in order to concentrate on the more promising double-exposure methods.

Preliminary tests were also made with a phototheodolite, the only other available camera designed for precise photogrammetric applications. With modifications the camera could be adjusted so as to make satisfactory measurements. However, for the lens and film available, a sufficiently fast shutter speed could not be obtained for dynamic loads, and actual deflection trials with the phototheodolite were not attempted. The larger focal length and plate size provided a better scale factor, and elimination of the built-in yellow filter and a special order of faster film could make the camera applicable to dynamic loading.

A new grid system for the targets was designed to simplify the calculations. By placing the lines of targets at an angle with the highway centerline and perpendicular to the optical axis of the camera, all points along the line were at the same scale factor (Figure 6). Horizontal distance from the camera to the target was obtained by direct measurement to the nearest 0.1 ft, producing a theoretical pavement deflection accuracy of 0.001 in. (for the camera, negative size, and distances used).

The most recent development in the use of photogrammetric methods for pavement deflections is double-exposure techniques. This procedure involves a

Figure 6. Angle placement of double-exposure targets.

complete departure from previous efforts using individual targets. The use of a double-exposure provides a convenient way of obtaining on a single photograph two profiles of a straight line referenced to a common datum. If the line moves between exposures, the profiles will not coincide (Figure 7).

The target line is defined by the intersection of a red and a blue plastic tape (Figure 6). The first photograph is taken when there is no load applied and the target is in the undeflected position (CE in Figure 7). By use of a blue filter, primarily blue light passes through the lens and only the blue part of the colored tape registers on the plate. For the second exposure, a red filter is used to permit the passage of the other half of the target. If a load is applied at the instant of the second exposure, the tape will be displaced to the position DF. An area on the film negative will not have been exposed if deflection has occurred, and a white line will appear. At the scale of the photograph, the white line is the image of the pavement deflection.

By placing the film plate perpendicular to the pavement surface, the image of the deflection will be parallel to the actual deflection. This system does repre-

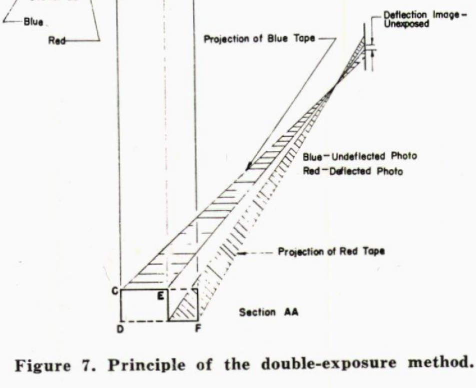

Figure 7. Principle of the double-exposure method.

sent an approximation because, although the plane of the optical axis is perpendicular to the negative, the optical axis itself is not perpendicular to the plate; therefore, a difference in scale factor exists between the upper and lower position of the image point. However, the scale factor is not critical within the degree of accuracy of ± 0.005 in. of true deflection.

The degree of accuracy required for the scale factor was computed on the basis of obtaining the deflection within ± 0.005 in. and within the accuracy of the measuring engine (± 0.002 mm). Values to the nearest whole number will be adequate for scale factors within the range of 10 to 20, and for pavement deflections of less than 0.3 in.

Computations of the scale factor were made on the basis of Eq. 4. The tapes were placed approximately perpendicular to the vertical plane through the optical axis of the camera. Thus, every point along each target line is to the same scale, within the accuracy of the degree of perpendicularity. Known lengths were designated on each end of the target lines and these lengths were measured on the photograph.

To compute deflections, the width of the thin white lines (appear black on the positive print in Figure 9) were measured on the glass plate using the Gaertner Measuring Engine. The uncorrected deflection is this measurement multiplied by the scale factor.

For correcting these measurements, only problems of outer orientation are involved. It was anticipated that the action of cocking the shutter would produce major camera movement. Such movement is recorded on the negative along with that of the pavement. Of the six types of movement that produces errors of outer orientation only the rotation of the camera about its optical axis (Y dimension) and the translation parallel to the Z axis (deflection dimension) are critical.

To measure the effect of these movements, stationary objects were located on opposite sides of the photograph. The amount of movement of these objects on the double-exposed film plate were measured, and a linear variation across the plate was assumed. On occasion, due to the absence of a stationary object in clear focus, points with known deflection were used; that is, the difference between the uncorrected measurements and the actual movement represented the correction required.

The amount of error was subtracted from the uncorrected values to obtain corrected deflection readings. In general, the correction was quite large, 0.05 to 0.10 in.

Laboratory tests were run to determine the accuracy to be expected with the double-exposure technique. A 1-ft by 8-ft piece of thin plywood was supported near each end and the middle. With the plastic tape in place, and three extensometers in contact with the target line, the setup was photographed. After the middle support was removed, the setup was again photographed. The deflection amounted to approximately 0.2 in. The results of these trials were encouraging (Figure 10). Four tests were run, and the two extensometers towards the extremities were used to measure camera movement. The four tests showed accuracies within .007 in. of the measured deflection.

An extended series of measurements were made on secondary roads in Franklin County, Ohio, during November 1956. Using double exposure techniques, a total of ten setups provided sufficiently sharp images to permit measurements. Additional photographs were taken, but preliminary focusing and lighting problems resulted in inadequate negatives. The field arrangements are shown in Figure 6. A Benkleman Beam and two standard extensometer dials were used for control purposes. Control measurements were available for direct comparison at 20 points. All photogrammetric measurements for which control checks were available are included in Figure 10.

A series of four double-exposure tests was conducted in early December on the Corps of Engineers' pre-stressed concrete test slab at Sharonville, Ohio. Figure 8 is a photograph of the test arrangement. Check measurements in this instance were LVDT readings and the Benkleman Beam. Deflection readings on the LVDT were as great as 0.250 in. under the 100,000-lb wheel load. However, focusing and target width problems prevented measurements in the area where deflection was of this magnitude. An enlargement of one of the Sharonville films is shown in Figure 9. The thin, dark line in the center of each target strip represents pavement deflection at the scale of the photograph.

The results of all of the field tests are

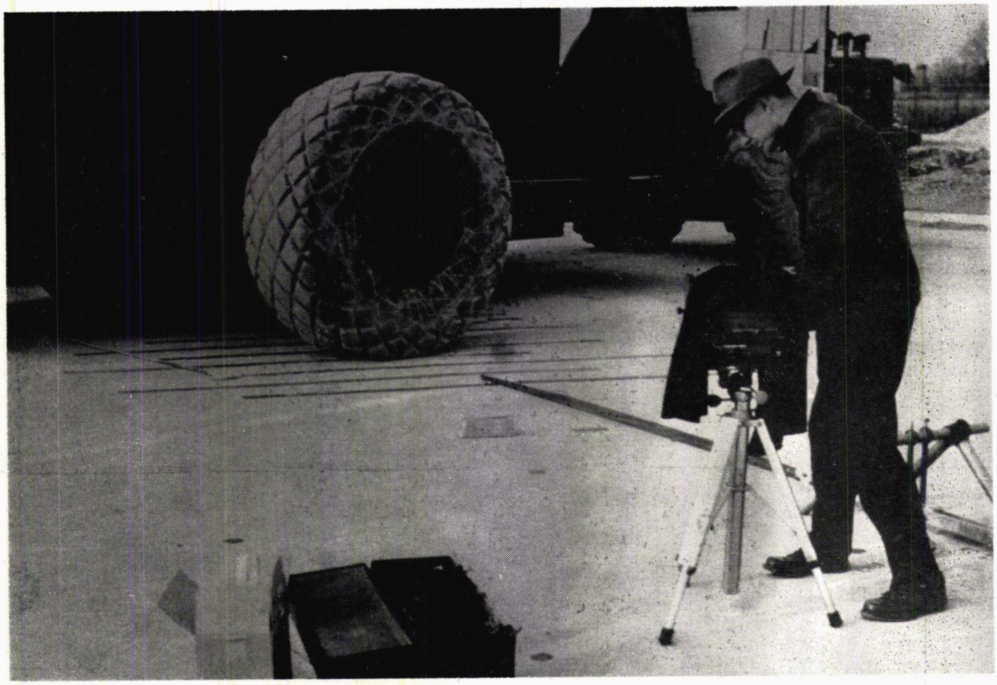

Figure 8. Field setup, Corps of Engineers' test slab at Sharonville, Ohio.

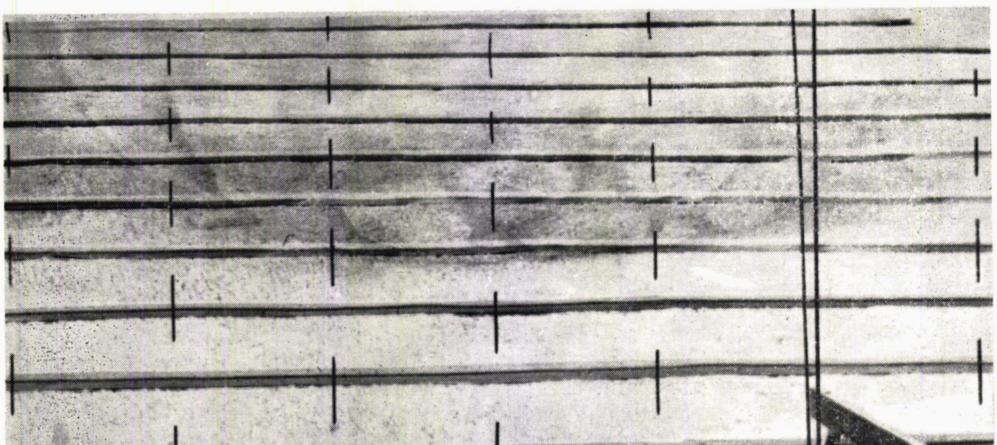

Figure 9. Enlargement showing thin, dark lines that represent pavement deflection.

summarized in Figure 10. The degree of accuracy was consistently within ± 0.005 in. The extremely bad points for which the photogrammetric measurement was too large are believed to be the result of inadequate error analyses, although possibilities of inaccurate dial readings do exist.

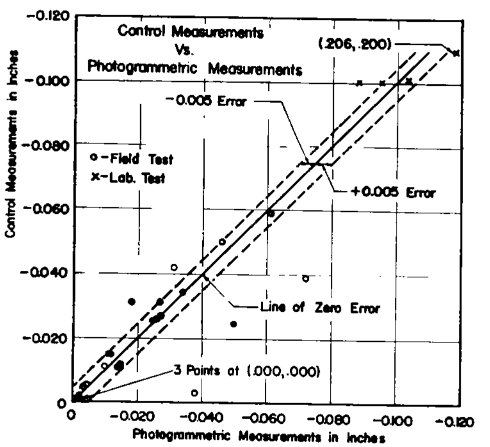

Figure 10. Evaluation of double-exposure results.

The camera used in these tests was a 5 x 7 Ansco View camera with a Kodak Commercial Ektar f/6.3 lens. The focal length of the lens is 8.5 in. The arrangement of the bellows in this camera permits the film plate to be kept approximately vertical while the lens is rotated about a horizontal axis through the lens center. The vertical position of the film is a necessary condition because the plane of the image should be parallel to the plane in which the deflection is measured. The film plate holder can be rotated through 90 deg, thereby permitting an increase or decrease of the field width of the photograph.

The film was 5-in. by 7-in. Kodak M Plates. These plates are coated with type B panchromatic emulsion which is sensitive to both red and blue lights and has a high resolving power. They are slow speed, high contrast plates, and the degree of contrast can be varied by varying the type of developer. The plates were developed in Kodak DK-50 developer to obtain a high contrast. The emulsion speed of the M plates in daylight is about ASA 32. This speed will not be satisfactory for most dynamic loads. Kodak Tri-X Panchromatic plates which have an emulsion speed of ASA 200 would be more suitable.

The photographs of the field tests were taken in daylight; the laboratory tests were taken under artificial light. One photo-flash bulb was used for each laboratory exposure. During most of the field tests the sun was bright, and it was possible to keep the camera exposure time at 1/50 sec. The f stop opening was set at 8 for the red filter and at 6.3 for the blue filter. The latter needed the larger opening because it was found that the blue tape reflected less light than the red tape.

The time requirements for the photogrammetric methods are favorable from the field testing viewpoint. Only ½ hr is required for two or three men to complete the layout. In the office, however, nearly two full days are required to obtain 20 to 30 deflection measurements.

RESULTS

The results using double-exposure methods are much better than those for individual targets. Many circumstances have contributed to this. However, error analyses which can be accurately accomplished on a single plate, as well as a better target, account for the major part of the improvement.

The early part of the field work was conducted from June to November, and the deflection produced by legal axle loads were in the range of 0.02 to 0.05 in. These small measurements served to complicate the development-type tests and the over-abundance of this size of measurement makes the validity of the degree of accuracy somewhat questionable.

The arithmetic mean of the errors for the measurements (Figure 10) is 0.0062. This is under the assumption that the control measurements were accurate to ± 0.0005 in. The standard deviation from the mean was 0.0095. The statistical relationships are not considered reliable because of the limited data available.

There was insufficient time to complete the measurements to produce deflection contours. However, as many points as are desired can be used for determining the shape of the surface deflection pattern. A significant part of the area of interest is behind the wheel from the camera, but if two cameras were used nearly 100 percent coverage could be obtained. One camera will provide sufficient data to permit reasonable interpolation, however.

The techniques of photogrammetry were developed for use with dynamic loads. However, because of easier field operations only four of the points on Figure 10 represent dynamic conditions. There was nothing encountered in these cases that would indicate any new problems related to dynamic loading.

Several developments are needed to simplify the procedure, to enhance the potential of the technique, and to provide more certain photographic results. The camera and the film should be examined with a view to improving the depth of focus, particularly for dynamic conditions. The measuring engine requires further evaluation in order to have more certainty as to reproducibility of readings.

Research is also needed to improve the method for analyzing the errors. Better techniques for measuring camera movement will produce more consistent accuracy.

The possibilities of enlarging the negative should be investigated. With larger dimensions to measure, the office procedure would be simplified by the reduction in accuracy required which in turn would permit less expensive equipment and more rapid operations.

CONCLUSION

The photogrammetric technique utilizing double exposure methods is considered adequate for measuring pavement deflection to an accuracy of approximately ± 0.005 in. Although continued development is needed, routine use of the double-exposure technique should be considered feasible.

The use of individual targets on two photographs is probably practical for accuracies of ± 0.01 in. Less accuracy should be anticipated than is possible with the double-exposure method.

The double-exposure technique does not require an expensive camera or elaborate equipment other than the measuring engine. Future research using photo enlargements might eliminate the necessity for the precise measuring device. For accuracies of the order of 0.05 in., less expensive equipment could be employed.

Continued research is desirable particularly with regard to the camera and film to be used. Focusing and shutter speed problems are troublesome. Better error analyses are needed, and improved techniques for measuring camera movement are essential.

It is not recommended that photogrammetric measurements supplant other methods of determining pavement deflections. Certainly if conventional, mechanical means are adequate, simplicity and economical advantage would call for their use. The Benkleman Beam will give valuable data under proper conditions. Electronic methods (LVDT or linear potentiometers) are essential on test roads, particularly where continuously recorded observations are desired. Photogrammetry will be useful as an adjunct for determining areal descriptions of deflections under dynamic conditions, particularly for medium to high speeds and for evaluations of existing pavements.

ACKNOWLEDGMENTS

The development of photogrammetric techniques for pavement deflection has been the result of the combined efforts of many individuals. The independent and earlier work of Turpin and Briggs has been mentioned. Frederick Doyle gave the technical guidance from the photogrammetric viewpoint. Robert Chieruzzi, Research Associate of the Engineering Experiment Station, contributed as associate supervisor in direct charge of the field tests and office analyses. K. S. Senathirajah developed the newest type of targets and designed the experiments using double-exposure techniques. Donald Bowser, of the University's Department of Photography, aided materially through developing the photographic procedures for the double-exposure method.

The staff of the Ohio River Division laboratories, through the cooperation of the director, Frank Mellinger, permitted tests to be run in conjunction with their full-scale test track for rigid pavements.

The encouragement of Robert S. Green, Executive Director of the Enginering Experiment Station, resulted in funds being made available for the conduct of the problem. Many persons, including students, laboratory technicians, and stenographers, aided in the study at various times.

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