FINAL REPORT

APPLICATION OF CLOSE-RANGE TERRESTRIAL PHOTOGRAMMETRY TO BRIDGE STRUCTURES

by

Marvin H. Hilton
Senior Research Scientist

(Photogrammetry by F. B. Bales,
Photogrammetric Engineer)

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SUMMARY

A field application of close-range terrestrial photogrammetry to the measurement of small order of magnitude structural displacements and differences in elevation was conducted. A Jena UMK 10/1318 camera was used to take the photographs used in the evaluations.

Measurements of the deflections of steel girders on several bridges suggest that accuracies on the order of 1/8 in can be achieved with normal care using the UMK 10/1318 camera. In addition, close-range terrestrial photogrammetry can be used for other bridge applications such as for deck condition surveys. By using this technique for condition surveys, the need for taking hand measurements and preparing sketches in the field is eliminated. The photographs provide a permanent record which can be used as a reference to evaluate potential changes in the condition of the deck or to gage structural movements. Where permanent records of bridge evaluations are desirable, the use of close-range photogrammetry should be considered.

The UMK 10/1318 camera produced satisfactory results during the study and has been purchased by the Virginia Department of Highways and Transportation for close-range terrestrial applications. It is recommended that highway and bridge engineers be made aware of the capabilities of close-range photogrammetry.

SI CONVERSION FACTORS

To Convert From	To	Multiply By
Length:		
in	cm	2.54
in	m	0.025 4
ft	m	0.304 8
yd	m	0.914 4
mi	km	1 . 609 344
Area:		
in^2	cm^2	6.451 600 E+00
ft^2	m^2	9.290 304 E-02
yd^2	m^2	8.361 274 E-01
mi^2	Hectares	2.589 988 E+02
acre (a)	Hectares	4.046 856 E-01
Volume:		
oz	m^3	2.957 353 E-05
pt	m^3	4.731 765 E-04
qt	m^3	9.463 529 E-04
gal	m^3	3.785 412 E-03
in^3	m^3	1.638 706 E-05
ft^3	m^3	2.831 685 E-02
yd^3	m^3	7.645 549 E-01

NOTE: $1m^3$ = 1,000 L

To Convert From	To	Multiply By
Volume per Unit Time:		
ft^3/min	m^3/sec	4.719 474 E-04
ft^3/s	m^3/sec	2.831 685 E-02
in^3/min	m^3/sec	2.731 177 E-07
yd^3/min	m^3/sec	1.274 258 E-02
gal/min	m^3/sec	6.309 020 E-05
Mass:		
oz	kg	2.834 952 E-02
dwt	kg	1.555 174 E-03
lb	kg	4.535 924 E-01
ton (2000 lb)	kg	9.071 847 E+02
Mass per Unit Volume:		
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lb/in^3	kg/m^3	2.767 990 E+04
lb/ft^3	kg/m^3	1.601 846 E+01
lb/yd^3	kg/m^3	5.932 764 E-01
Velocity: (Includes Speed)		
ft/s	m/s	3.048 000 E-01
mi/h	m/s	4.470 400 E-01
knot	m/s	5.144 444 E-01
mi/h	km/h	1.609 344 E+00
Force Per Unit Area:		
lbf/in^2	Pa	6.894 757 E+03
lbf/ft^2	Pa	4.788 026 E+01
Viscosity:		
cSt	m^2/s	1.000 000 E-06
P	Pa·s	1.000 000 E-01

Temperature: °F-32)^5/9 = °C

APPLICATION OF CLOSE-RANGE TERRESTRIAL PHOTOGRAMMETRY TO TO HIGHWAY BRIDGES

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Senior Research Scientist

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INTRODUCTION

Photogrammetric surveying involves obtaining information in an indirect manner by taking measurements from photographs of an object. Unlike conventional surveying procedures where measurements are usually made directly of the object in the field, photogrammetry involves recording the area on photographs and using these to obtain the required measurements at a later time in the office. When photogrammetric techniques are used, three general operations are required. These are planning and taking the photographs, processing the photography, and, finally, using the photographs to obtain the desired measurements. The photographs, for example, can be used to produce other products such as topographic maps.

There are a number of uses for photogrammetry. In a broad sense it can be used for qualitative (interpretative) as well as quantitative (metric) work. Because of this diversity, photogrammetry has been found to be useful in a number of fields beyond its most common applications in surveying and mapping. Some of these fields include forestry, all types of engineering, biomedical, astronomy, physics, transportation and urban planning.(1)

Metric photogrammetry can be divided into two areas: aerial and terrestrial. In aerial photogrammetry a high precision camera, which is mounted in an airplane, is used to photograph an area as the plane flies over. For terrestrial photogrammetry, photographs are taken from fixed positions either on or near the earth's surface. While the majority of the photogrammetry work conducted in the highway and transportation field has been of the aerial type, the work presented in this report is concerned with an evaluation of some potential applications of terrestrial photogrammetry to highway bridges.

The use of photogrammetry in this particular study can be further defined as close-range terrestrial photogrammetry. In these type applications the camera is mounted relatively close to the object to be photographed. Photogrammetry is considered to be close-range when the camera-to-object distance is in the approximate range of 4 in to 330 ft.(2) Photogrammetry in this range is used in many fields where direct measurement of an object is either costly, impractical, or very difficult if not impossible to obtain otherwise.

In highway and transportation engineering there may be a number of applications for close-range terrestrial photogrammetry. These may range from documenting historically significant structures to measuring small distances such as structural movements, deflections of structural members, or other changes in the relative positions of structural elements.

PURPOSE AND SCOPE

The primary purpose of this study was to evaluate the applicability of close-range terrestrial photogrammetry for the measurement of small structural movements such as the deflection of bridge members. Several secondary purposes of the study were as follows:

1. Review the background and some precedents for the use of close-range terrestrial photogrammetry for obtaining engineering measurements of bridges.

2. Review the general classification of cameras used in terrestrial applications.

3. Evaluate the particular camera used to accomplish the primary purpose of the study.

4. Evaluate the use of close-range terrestrial photogrammetry for recording bridge deck condition surveys.

5. Evaluate the ability of the technique to define small differences in elevation such as that associated with the surface texture of bridge decks.

The scope of the study was limited to the field and office work necessary to accomplish the above objectives. Several bridges, which are described in more detail later, were selected for field study. An analysis of the resulting photography was made by the photogrammetry section of the Virginia Department of Highways and Transportation.

BACKGROUND

Close-range photogrammetry has been used over a relatively long period of time, beginning in the middle of the nineteenth century. In the earliest applications terrestrial photographs were used by surveyors to develop maps from a point-by-point intersection technique. It was difficult, however, to identify the same point on different photographs. This problem was resolved by the invention of the stereo comparator, which resulted from the independent work of Pulfrich in 1901 and Fourcade in 1903.(3) This device made possible the simultaneous setting of identical measuring marks on photographs of two different views. Succeeding calculations were made by the point-by-point method, but this work has subsequently been automated.

In 1885 close-range photogrammetry was applied to architecture when Meydenbower began the photogrammetric monument archive in Germany.(3) Architectural photogrammetry is now widely used to aid in reconstruction efforts after damage and for other measurements related to restoration work. In 1889 photogrammetry was used to survey glaciers. The possibility of using the technique to observe changes in the size and velocity of glaciers was recognized, and thus the time dimension was added to the analysis of photogrammetric measurements. Other early applications of close-range photogrammetry at the turn of the century included the evaluation of X-ray images taken for medical purposes.

Up to the 1920's the development of photogrammetry dealt with photographs taken from ground stations. Subsequently, however, the main emphasis was placed on the development of both the aerial photography and the stereoplotting instruments that are used to produce useful data from aerial photographs. With more recent attention given to applications of terrestrial photogrammetry in a variety of technical areas, it is again being recognized as a method that can be used for obtaining measurements of objects and for documentation purposes. Federal legislation in recent years, for example, has placed restrictions on the use of federal funds for construction and other engineering activities that may affect historically significant sites or structures. When a site or structure is either included on, or is eligible for inclusion on, the National Register of Historic Places, an effort must be made to prevent harm to the site. In some cases where the only alternative is demolition or removal, it is often required that records of the structure or object be acquired. This kind of documentation could often require time-consuming and laborious field measurements and the subsequent drafting of drawings. In addition, an inventory of bridge structures within each state transportation department is now encouraged so that historically significant structures can be identified. It is apparent that close-range terrestrial photogrammetry could be used to assist in satisfying these requirements. The applicability of using this approach to document historically significant structures and objects associated with transportation projects was evaluated in Virginia in a recent report by Spero.(4) It was concluded in this work that documentation by photogrammetric methods is sufficiently accurate and is very cost-effective. It was also noted that obtaining field data by photogrammetry is not labor-intensive, whereas the use of more traditional methods normally is very labor- intensive. It was further recommended that a camera that could be used for close-range terrestrial photogrammetry be purchased. Subsequently, the camera that was used on the study by Spero and on the work being presented in this report was purchased by the Virginia Department of Highways and Transportation. This camera is described later.

The use of terrestrial photogrammetry to measure distortion and movement in bridges is not without precedent. Distortion and deflection of a structure as a function of time can be determined by monitoring on a regular basis. Accordingly, an account of the use of photogrammetry to measure movement in a box girder bridge was presented by Scott in 1978.(5) The measurement of the distortion of an arch caused by the settlement of a railroad bridge has also been described.(3) In this latter instance photogrammetry was used to develop the contour of the distorted arch so that an armored lining could be constructed to fit and support it. In another recent instance, two Jena UMK 10/1318 cameras were used on a bridge in Germany to determine the exact measurements of the structural elements at the bearings so that new bearings could be fabricated. The use of other techniques would have required the railroad bridge to be closed for unacceptable periods of time and would have been more costly.(6) In a still more recent case, the Williamsburg Bridge across the East River in New York City was surveyed using photogrammetric techniques to determine the condition of the corroded suspension cables and to get an accurate bridge profile during load tests. Two advantages of using the technique on this bridge were cited. First, considerable time was saved and the bridge was closed for only a few hours, whereas the use of other techniques would have required many days. Secondly, the stereophotos record considerable data that can be reexamined at any time to obtain additional information.

CLOSE-RANGE PHOTOGRAMMETRIC CAMERAS

General Classification

The camera is the initial instrument used in the total photogrammetric system and is similar in function to surveying instruments since it is used to obtain information about an object. Whereas a transit or theodolite can provide information in only one direction for a given sighting, a photograph can yield information in a virtually unlimited number of directions. Therefore, any point identified on the photograph would represent a different direction with respect to the camera position. The camera is thus an important instrument since good quality photographs are necessary to assure metric accuracy.

It should be noted that the cameras used for terrestrial photogrammetry differ from those used for aerial surveys. Since in terrestrial photogrammetry the camera is used from stationary positions, its design is simpler than that of a camera used for aerial surveys. The camera is combined, in effect, with a theodolite (phototheodolite) and is used to obtain photographs of an object from fixed control points. In order to obtain overlapping photographs the phototheodolite must be moved from one station to another, or two cameras mounted at a known distance apart on the ends of a rigid base could be used to obtain the stereo pairs of photographs. Aerial cameras, on the other hand, being in motion during exposure, require a fast lens, a good shutter mechanism for short exposure times, and a film with a high-speed emulsion. Since this project was concerned with terrestrial photogrammetry, aerial cameras will not be discussed further.

The cameras that are used for close-range terrestrial photogrammetry are designated as either metric or nonmetric. Nonmetric cameras have an interior orientation that is unknown and is often unstable; i.e., the principal point and principal distance illustrated in Figure 1 are unknown or unstable. Metric cameras, on the other hand, were once assumed to have a fixed interior orientation. With the development of focusable cameras having tolerable radial distortion and stability, it was no longer adequate to designate only the cameras having a fixed orientation as being metric. It has been suggested that the simplest way to classify a camera as being metric is by the existence of fiducial marks.(3)

Nonmetric cameras normally are not designed specifically for photogrammetric work and must be calibrated in some way if they are to be used for such work. Used in combination with an appropriate data reduction system, nonmetric cameras can provide highly accurate results and are less costly than metric cameras. Several data reduction schemes have been reported by Karara.(3) In a general sense, a nonmetric camera can be obtained for low cost, but an expensive evaluation system requiring a sophisticated computer program would be required. The metric camera is more costly, but the photographs taken with the instruments can be restituted with analogue plotters. The availability of the plotters would appear to make the metric camera the more logical choice for most projects that require that measurements be derived from the photographs.

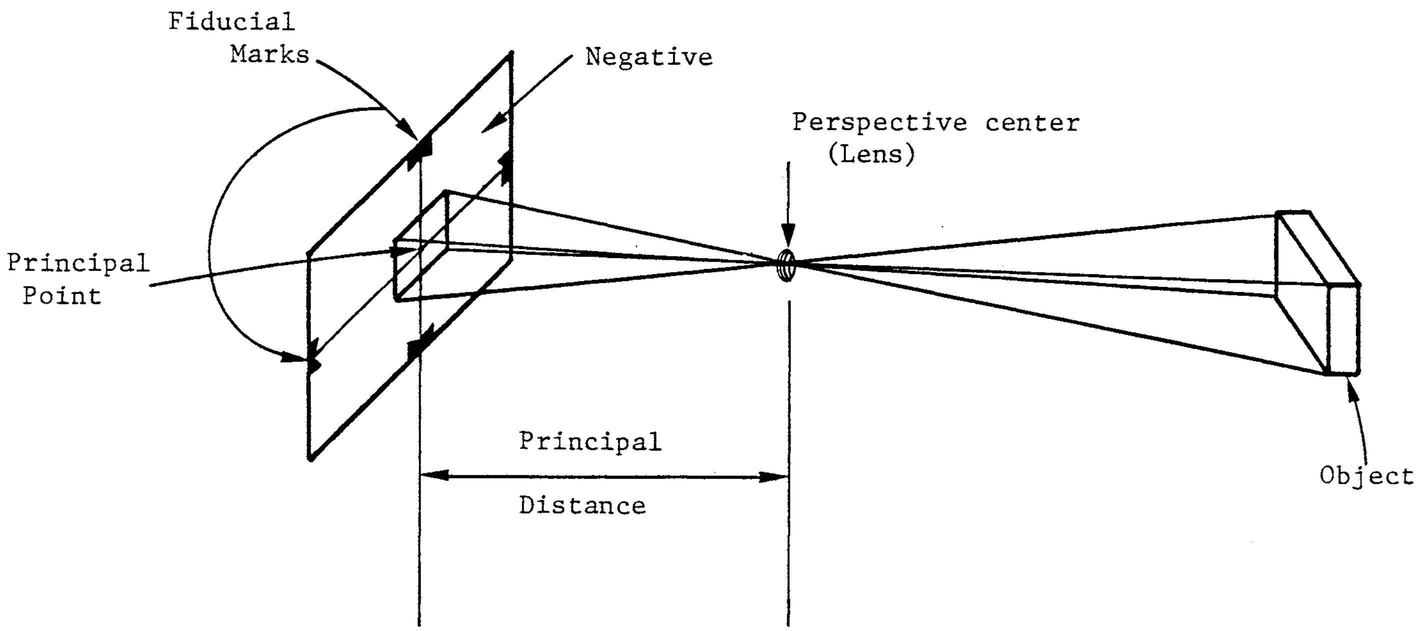

Figure 1. Illustration showing principal distance, principal point, and fiducial marks. (From Ref. 3.)

Cameras used for metric work are called "cartographic" cameras and are usually characterized by lenses highly corrected for geometric distortion.

The UMK 10/1318 Camera

The camera used in this study and the study reported earlier by Spero(4) was the Zeiss (Jena) model UMK 10/1318. This single metric camera is mounted in its own orientation device. Two views of the UMK 10/1318 mounted in its orientation device on a tripod are shown in Figures 2 and 3.

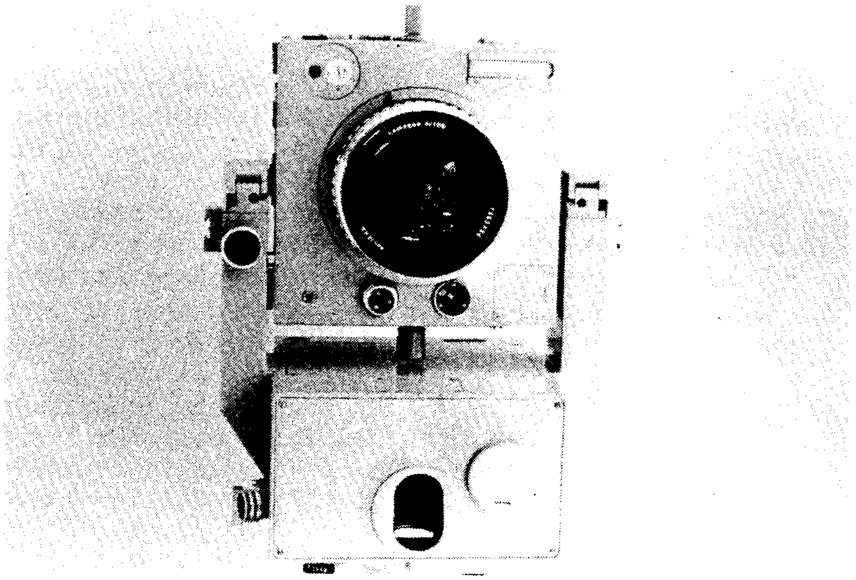

Figure 2. Front view of the Zeiss (Jena) UMK 10/1318 Universal Photogrammetric Camera.

Figure 3. UMK 10/1318 camera being placed on tripod for field use.

The UMK 10/1318 can be efficiently used where a wide-angle field or a large size picture is required. Objective focusing allows the taking of photographs between distances of less than 1.5m and infinity. The camera offers continuous focusing of the objective lens, a large range of exposure times and stop-settings, a choice of horizontal or vertical format, and a choice of horizontal or vertical photographic axis. The camera and its substructure can be separated to facilitate handling and operation. Angles can be measured with a high degree of precision with the orientation system. Other features of the camera include an electromagnetic shutter release and electrical illumination of the fiducial marks. Use of the UMK 10/1318 with a second universal camera in a double-mounted configuration is possible where the erection of two single tripods would be difficult. The UMK 10/1318 is probably one of the most versatile of the cameras available for use in close-range terrestrial photogrammetric applications. Some of the main features of the camera are summarized in Table 1. As noted in Table 1, either film or plates can be used for taking photographs. For the purpose of this study, glass plates were used to eliminate the image distortion that can occur with temperature changes and shrinkage associated with film.

In photogrammetric studies the photographs can be defined as being horizontal, vertical, or oblique by nature of the orientation of the optical axis of the camera. Accordingly, when the camera axis is horizontal the photographs will be defined as being horizontal, and so on. Horizontal and vertical photographs can be analyzed with stereoscopic plotting instruments that are commonly used for aerial photography and were available for the study. Oblique photographs require universal or analytical stereoplotters for accurate restitution. A universal stereoplotter was not available for this study. However, only horizontal and vertical photographs were necessary to accomplish the main objectives of the work.

Table 1

Summary of Main Features of the Zeiss (Jena) Model UMK 10/1318 Single Terrestrial Camera

Nominal focal length (mm)	Principal distance	Format (mm)	Minimum range (m)	Tilt range (deg)	Photographic material	Position of principal point	Format rotation
100	Variable in steps	130x180	1.4	-30 to +90	Plates or film	Central	Yes

Source: Ref. 3.

MEASUREMENTS FROM PHOTOGRAPHS

In photogrammetry the photographs normally are taken such that there will be a 60% overlap in the object area being observed. Thus, if a pair of adjacent photographs are viewed from two positions, objects lying in the overlapped area can be seen in three dimensions.

To develop the geometry of overlapping photographs a stereoplotter is used. It is a high-precision instrument that can be used to obtain accurate three-dimensional information about the photographed object. This is accomplished when two overlapping photographs are placed in the device such that the relationship between the camera field stations is reproduced very precisely. Basically, the photographs are correctly aligned in the stereoplotter when the optical axes are positioned as they were when the photographs were taken. The optical axis for a photograph is located by the use of four fiducial marks (shown earlier in Figure 1) that are recorded on the image at the time of exposure. The intersection of lines drawn through the opposite fiducial marks will locate the principal point (Figure 1). When the principal point is directly over the optical axis of each of the two projectors of the stereoplotter the interior orientation for each overlapping photograph is recovered. With the interior orientation recovered, the light rays passing through the plates will be a replica of those that entered the camera when the photographs were taken. The relative position and orientation will not duplicate the situation existing at the time of photography, however, until the exterior orientation elements have been recovered. Each of the photographs in the stereoplotter must be positioned with respect to the X, Y, and Z axes. As a result, six degrees of freedom, which include three translations and three rotations, have to be recovered for each overlapping photograph. In order to accomplish this orientation, an adequate number of survey control points must be provided.

Relative orientation solves for five orientation elements and can be accomplished by manipulating the stereo model such that it is established at an arbitrary scale. It, in effect, causes each pair of corresponding rays to intersect at a point by recovering the relative tilts of the two projectors with respect to each other. Absolute orientation solves for seven orientation elements and is accomplished by scaling and leveling the model. For scaling, two horizontal control points are plotted on the drawing or map at the scale to be used. The control points are used to make the horizontal distance between the corresponding photographic model points equal to the distance on the drawing or map. This is done by changing the model base in the instrument. For leveling, at least three vertical control points are needed to establish a plane. The four corners of the stereo models quite often are used, however, and front to back and side to side rotations are conducted to make the stereo model level. The two operations of scaling and leveling are alternately repeated as necessary to refine the results, since one adjustment may affect the other.

When the exterior orientation is recovered, the resulting stereoscopic model can be measured by a tracing table which can be moved through the model space in all three directions. All three motions can be monitored and recorded either manually or automatically. When viewing the model stereoscopically through colored spectacles attached to the tracing table, the operator sees within the model a circular white floating dot which can be used to determine differences in elevation. This is accomplished by moving the floating white dot vertically until it appears to be in contact with a point on the object. Thus, if one wanted to trace the elevation of a sloping terrain, the elevation of the floating dot would have to be continuously changed to maintain apparent contact with the surface. To plot a contour, a line of constant elevation, the floating dot is fixed at the elevation in question and the tracing table of the stereoplotter moved in the horizontal plane. By keeping the dot in contact with the terrain surface, a line of constant elevation can be traced. Discrete points on the model can be measured to determine their elevation. In the case of time-dependent measurement of distortion or deflection of structures, photographs are taken of the object, and at a latter time additional photographs are taken at the same locations. Changes in elevation occurring during the time interval can thus be measured from the before and after photography.

ACCURACY

Accuracy is one of the main concerns of engineers in the measurement of distances, differences in elevation, or structural movements. This is particularly true in the case of the measurement of structural deflections that are expected to be of only a small order of magnitude.

The accuracy that can be obtained from photogrammetric techniques depends upon a number of factors such as the nature and quality of the camera, the quality of the photographic materials, the camera-to-object distance, and the disposition of the control points, to name just a few. Consequently, it is not possible to state accuracies that will be applicable to all situations. Generally, however, accuracy is directly related to the scale of the photograph. For a camera having a given focal length, the photo scale is a function of the camera-to-object distance. Hence, accuracy is usually expressed as a function of the photo-taking distance. For average conditions, an accuracy of ±0.01% of the camera-to-object distance can be achieved. Accordingly, at a distance of 50 ft, one could obtain an accuracy to within 1/16 in. Normally, in order to minimize the cost of the technique, only the degree of accuracy that is necessary is sought. It has been indicated that most industrial applications of photogrammetry aim for an accuracy of about ±0.02% of the photo-taking distance.(3) At any rate, it is apparent that remarkable accuracies can be obtained with close-range photogrammetric measuring techniques.

RESULTS OF FIELD APPLICATIONS

Bridge Deck Condition Survey

One possible application of close-range terrestrial photogrammetry is in photographically recording bridge deck condition surveys. These surveys are conducted on bridge decks that are to be repaired, reconditioned, or replaced. In order to determine the degree of repair or rehabilitation necessary, on-site examinations of the bridge decks are conducted. The on-site examinations involve mapping the areas on the deck surface where various types of distress are located. Areas of delamination, for example, usually are detected by the use of a chain drag, a sounding hammer, or both. The extent of the delamination is marked off on the deck and also recorded on sketches. Patches, scaling, and other evidences of deterioration are also located and recorded on sketches. In addition, cores are taken from certain locations on the decks and examined in the laboratory to determine chloride contents. Using all of this information, the distressed regions on the deck can be calculated, and using this information along with the results of the chloride analyses, a decision on rehabilitating or replacing the bridge deck can be made.

To evaluate the use of close-range photogrammetry for bridge deck condition surveys, a bridge that was scheduled for evaluation was selected for study. The bridge is located on Rte. 33 east of Harrisonburg and overpasses Interstate 81. It is composed of four simple spans (two 52 ft 7 in approach spans and two 68 ft 6 in center spans), and has a roadway width of 39.5 ft between curbs. The regular bridge deck condition survey crew conducted its work in the usual fashion, laying off the deck in a grid pattern and marking off delaminated and distressed areas as they were detected. After several of the spans were surveyed and marked the photography was begun, so that the traffic control could be used by the photogrammetry party as well as the deck survey crew. A base line was established on the deck of the bridge such that the entire width could be covered in each photograph. Targets were laid out on the deck at 26-ft intervals based on the needs for the mounting height of the camera and its focal length. Three lines of targets were placed on the deck, one on each side of the bridge and another approximately in the center of the two lanes that were closed to traffic during the operation.

The camera was mounted in a plywood frame attached to the bucket of a lift boom (Figure 4). The camera was operated at a height of 36 ft above the bridge deck. The truck and the bucket were moved to allow positioning of the camera above the center reference targets. A total of eleven overlapping photographs of the bridge deck were taken. A mosaic of these photographs is shown in Figures 5 through 8, which gives a complete view of the deck of the bridge beginning from the west end. As can be noted from these figures, the distressed areas were marked with crayon. A dark blue and a white chalk were used to determine which was the easiest to see on the photos. Probably the darker color is best, but either is acceptable.

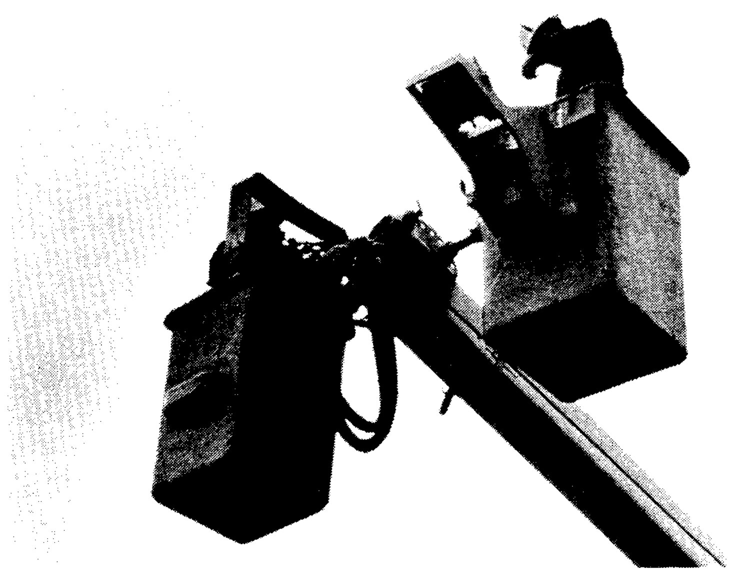

Figure 4. Camera mounting on the bucket of a lift boom for close-range photographing of a bridge deck.

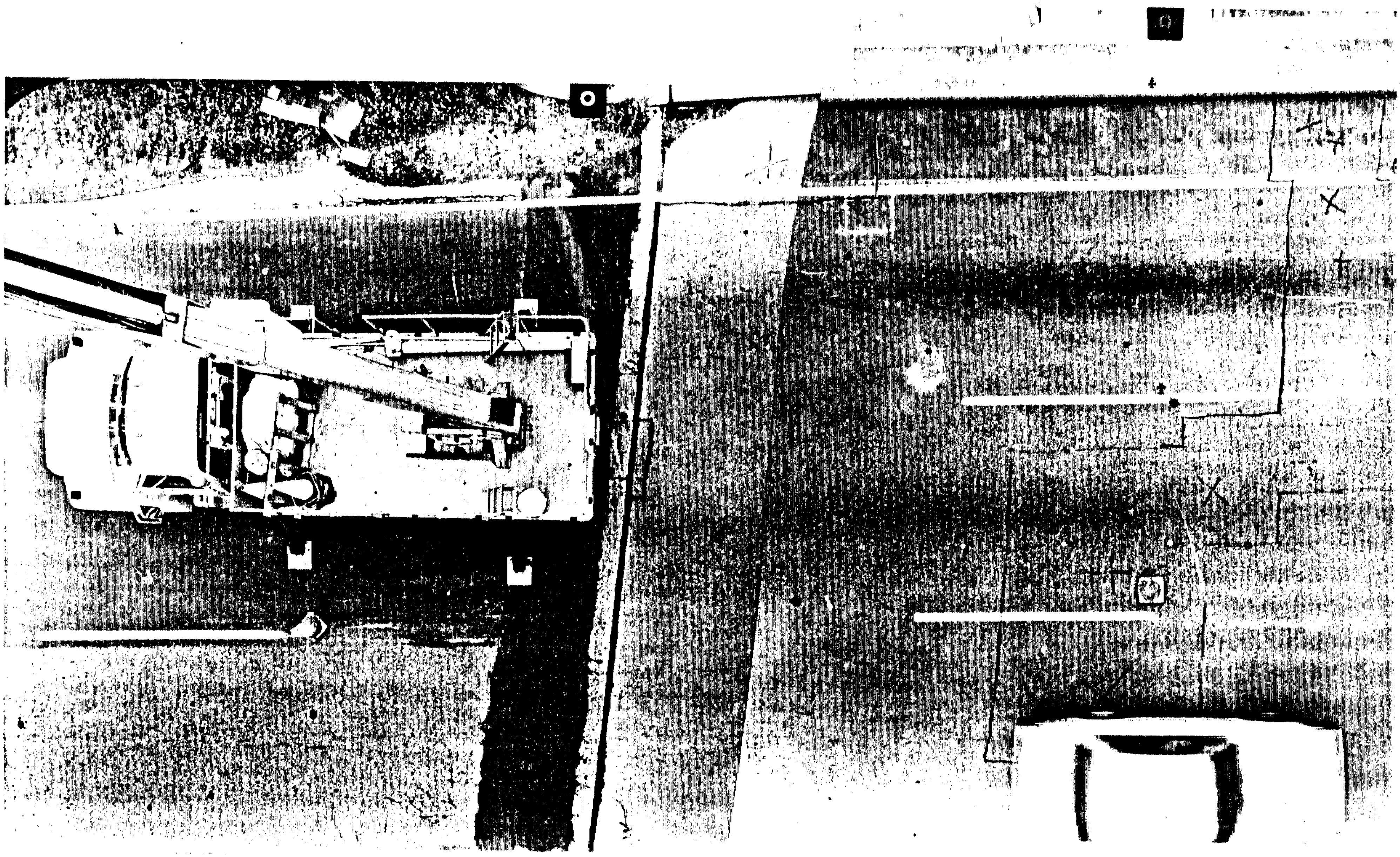

Figure 5. West end of Rte. 33 bridge over Rte. 64 showing truck and mast arm which supports the camera.

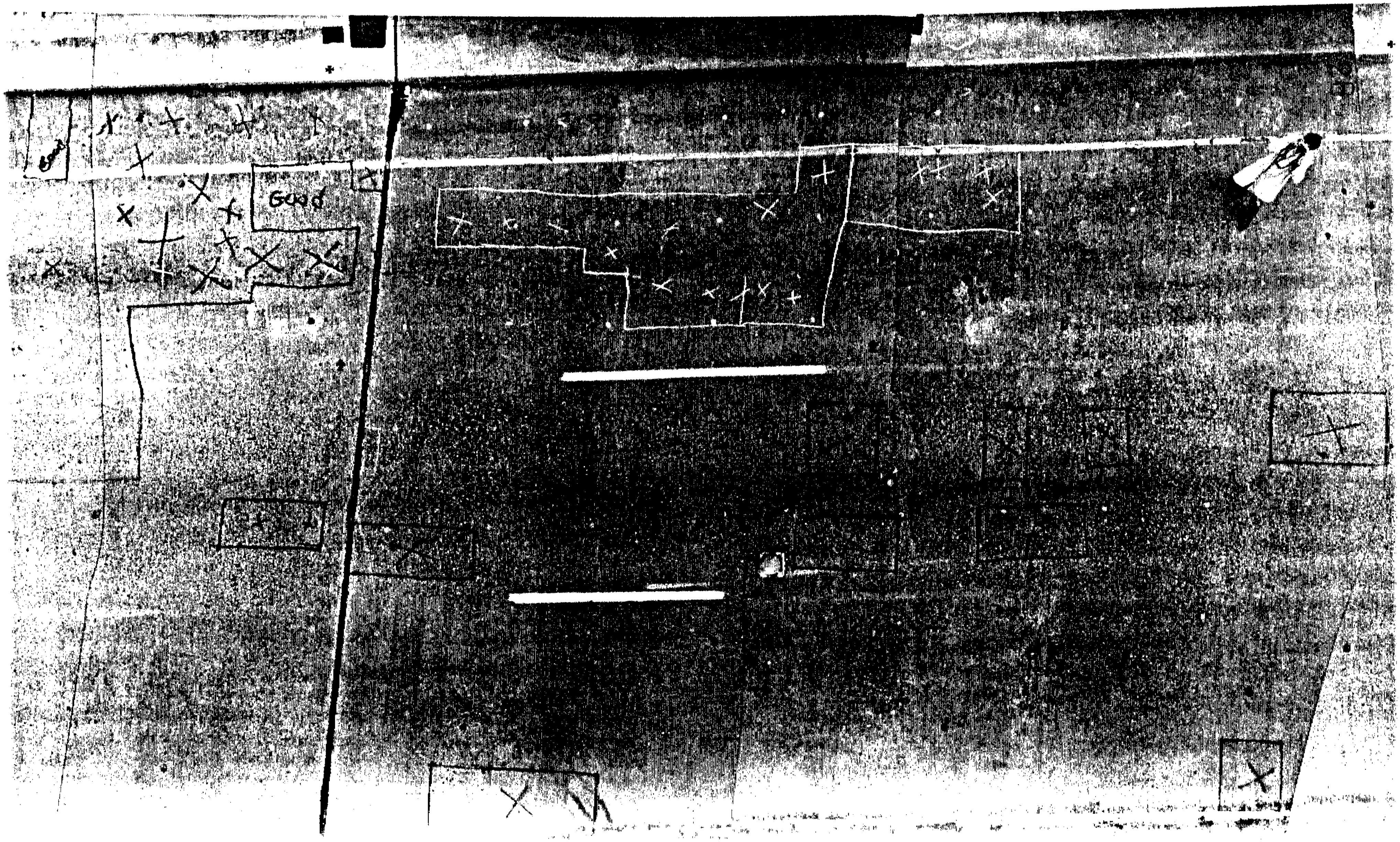

Figure 6. Continued mosaic of the Rte. 33 bridge deck.

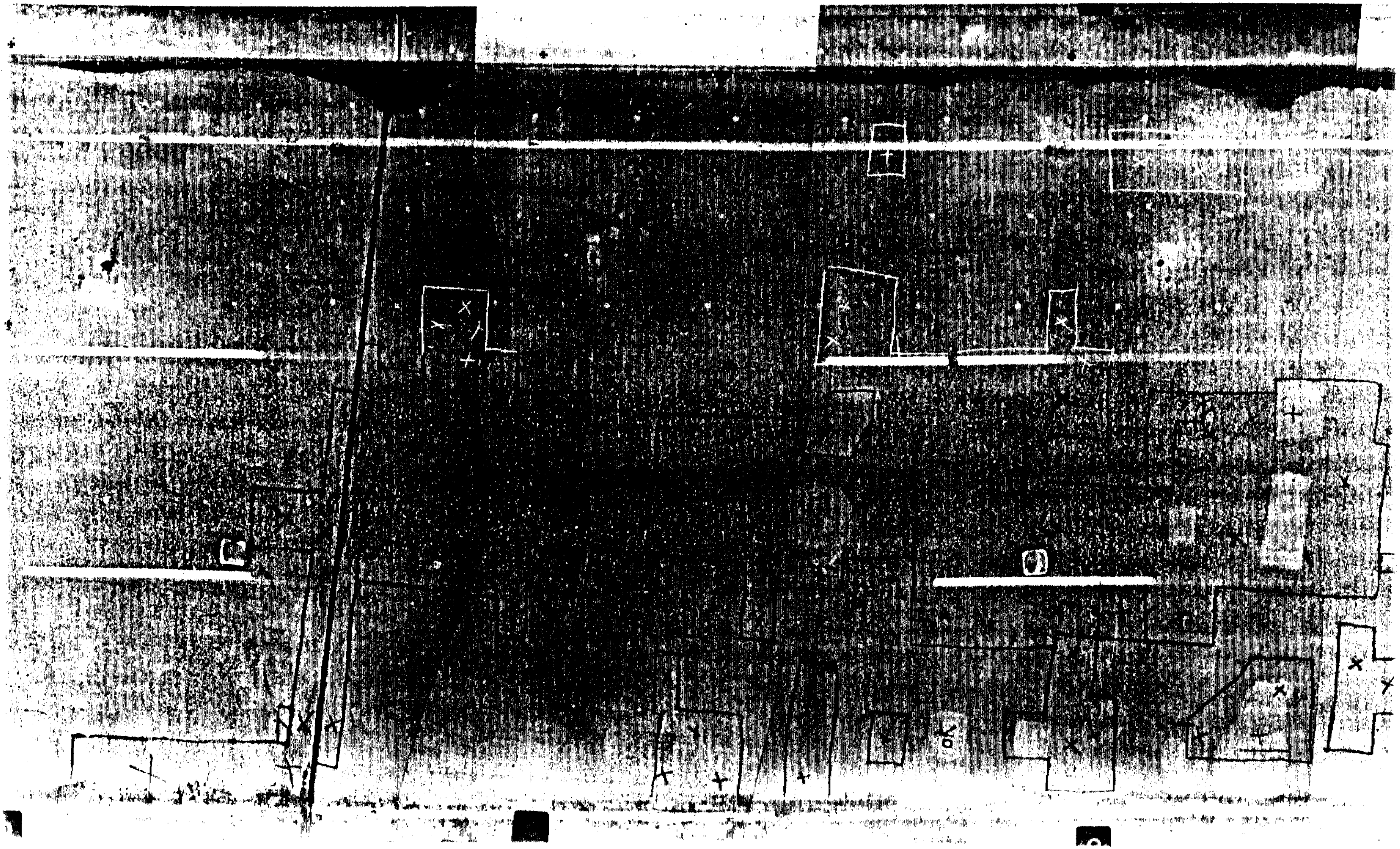

Figure 7. Continued mosaic of the Rte. 33 bridge deck showing span 3.

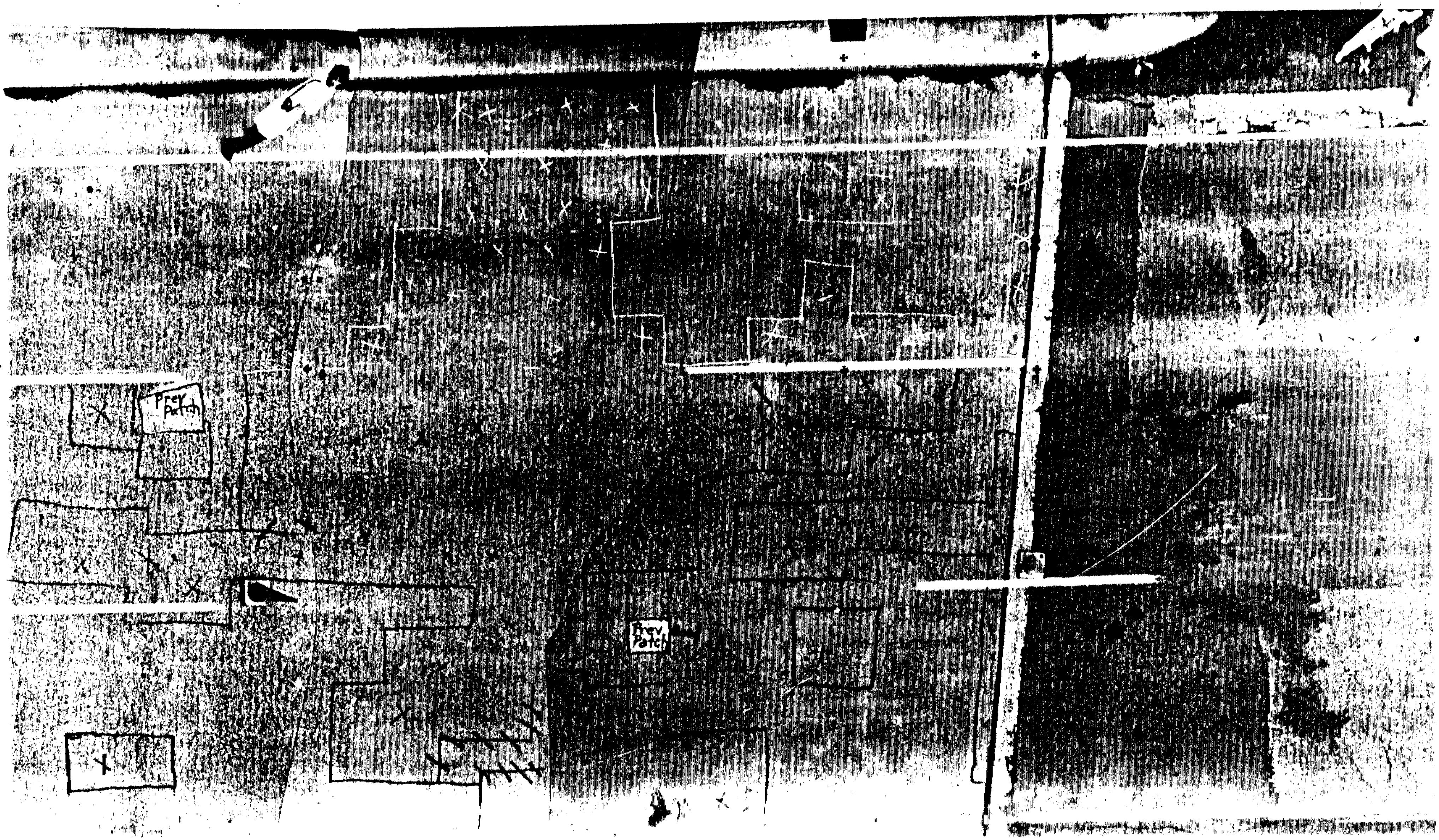

Figure 3. Continued mosaic of the Rte. 33 bridge deck showing span 4.

All of the edges of the delaminated areas were measured by the deck survey crew and this information recorded on their sketches. Thus, the recorded data could be used later to calculate the area of distressed material that would require removal if the deck were to be rehabilitated. If the deck were photographed, however, these measurements would not have to be taken in the field, since the area of the distressed material could be determined from the photographs. Figure 9, for example, shows the distressed regions of span 3 (Figure 7) plotted to scale from the photographs. The area in square feet of each distressed region is shown on the plat. It is interesting to note that the lighter colored patches on the deck shown in Figure 7 are spots that had been repaired in an earlier rehabilitation of the deck. Although these patches were not outlined on the deck, they were easily plotted as shown by patches marked with the broken lines in Figure 9. Several of these patches were measured and their areas calculated and compared with the areas determined from the photographs. The values were in very close agreement, but it is likely that the areas determined from the photographs are more precise than those calculated from the direct measurements, because at deck level it is sometimes more difficult to define the edges of some of the patches than it is from the photographs.

The use of close-range photogrammetry for bridge deck condition surveys can eliminate the need for developing sketches of the deck and for taking linear measurements of any type. In addition, a permanent record of the deck surface is available for future reference and use. Visual information such as that described above can be obtained from the photographs if needed, and possible future structural settlement or other changes in elevation or relative position can be measured by making use of the initial photographic record. Having a permanent record for future use might be the primary reason for using close-range photogrammetry for a bridge deck condition survey. While use of the technique could reduce some of the work and thus the manpower required for the survey, this would be offset by the need for photogrammetry personnel and a lift bucket truck and operator.

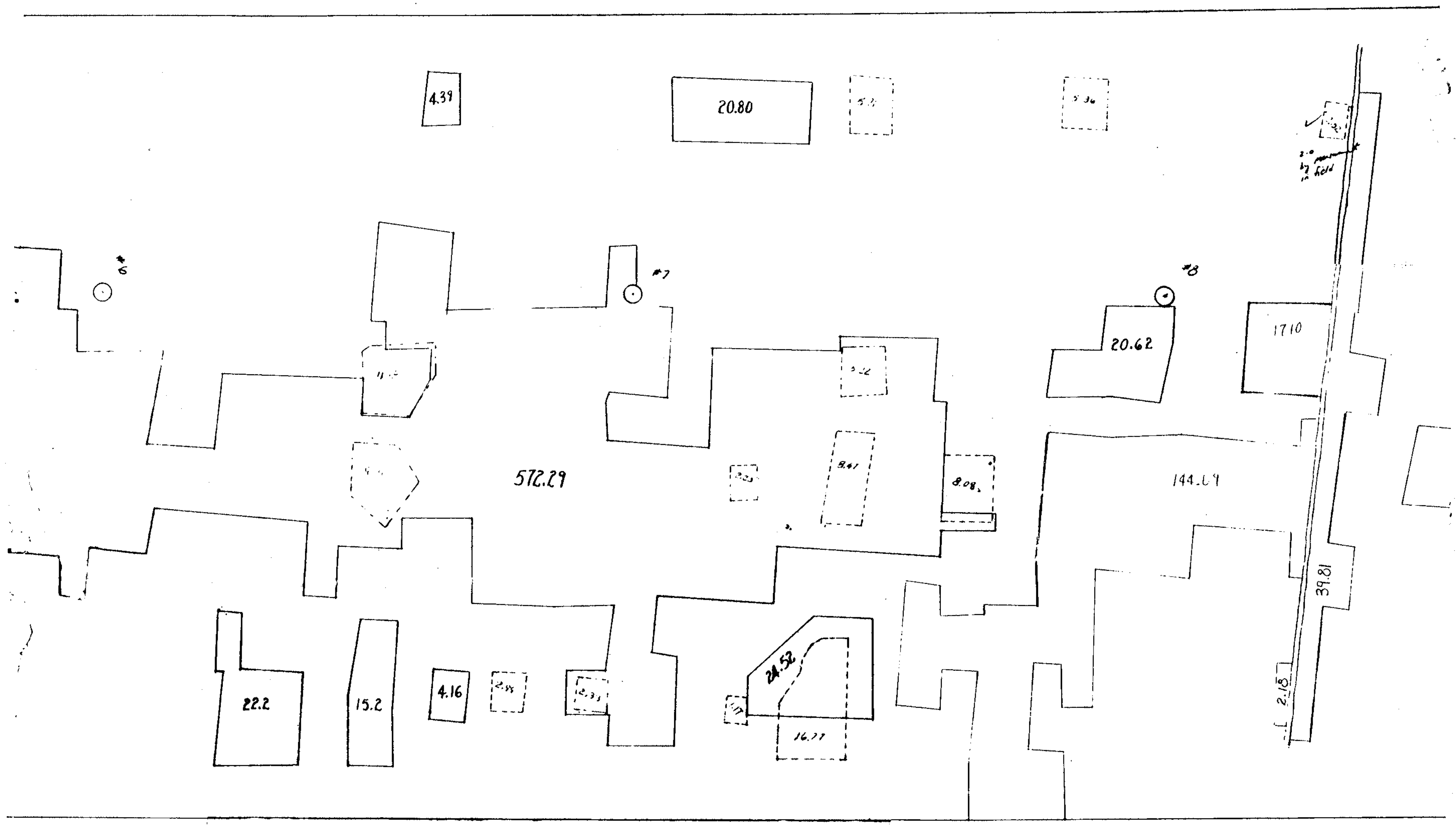

Figure 9. Distressed areas of span 3 plotted from photographs of deck. Areas indicated by broken lines were repaired in earlier deck rehabilitation.

Differences in Elevation of Surface Irregularities and Cracks

Several points on the deck of the bridge described above were selected for the purpose of determining small differences in elevation. At three locations the photogrammetric engineer measured the depth of the joint filler relative to the highest surface level of the deck immediately adjacent to the joint (Figure 10). At four other points, he made similar measurements of the depth of some small pitting in the deck surface. Finally, he measured the widest widths of three cracks near several of the bridge deck joints. All of these measurements were taken in the field to the nearest 1/16 in by using a straightedge and rule. The photogrammetric engineer independently determined the distances to the nearest 0.01 ft. The field measurements were subsequently converted to the nearest 0.01 ft and compared with those determined from the photographs as shown in Table 2. Of the ten selected measurement comparisons, four were the same, five differed by 0.01 ft, and one differed by 0.02 ft. All of the vertical measurement comparisons were within 1/8 in or less. The photogrammetric measurements were taken only to the nearest 0.01 ft (i.e. approximately 1/8 in), but it is apparent that very exacting measurements can be obtained with the close-range photogrammetric technique. Measurement within 1/8 in of the actual value are sufficiently accurate for most highway and bridge applications.

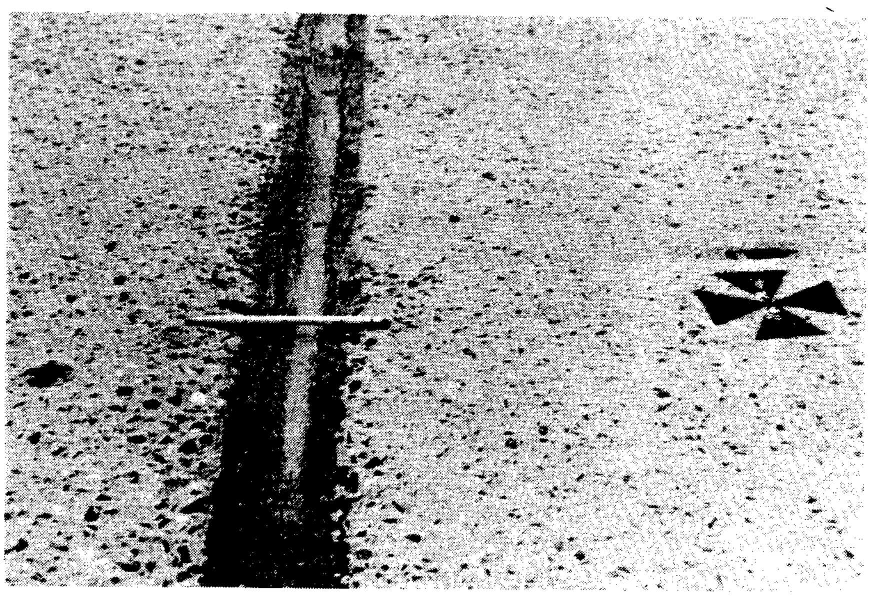

Figure 10. Relative depression of joint filler.

Table 2

Comparison of Some Selected Field and Photogrammetric Measurements

Description of Location	Field, Ft	Photogrammetric, Ft	Difference, Ft
		Measurements	
Joint depth 1	0.06	0.06	0.00
Joint depth 2	.05	.06	.01
Joint depth 3	.05	.05	.00
Surface pit 1	.03	.02	.01
Surface pit 2	.03	.03	.00
Surface pit 3	.03	.02	.01
Surface pit 4	.03	.02	.01
Crack width 1	.05	.07	.02
Crack width 2	.05	.06	.01
Crack width 3	0.08	0.08	0.00

The surface irregularities of a bridge deck can also be developed from photographs. One way of showing the very small deviations in the surface of a bridge deck is to develop contours spaced at a close interval. For this test of the technique, the Rte. 64 bridge over Rte. 639 in Allegheny County was selected for study. A 0.05-ft contour interval was used to evaluate the use of contours for defining surface roughness from the photographs, and the results are shown in Figure 11. The crown of the deck is shown by the rightward pointing of the contours at the upper center of the figure. Ideally, a perfectly smooth transverse slope on a bridge deck would be represented by a straight contour line from the crown to the edge of the deck. Furthermore, the horizontal spacing between the contour lines would be the same for all the contours shown. Thus, the nonlinear contour lines and the variation in width between adjacent contours show the surface roughness, or irregularities, in the surface of the deck. Deviations from linearity along the contour lines show the relative degree of roughness at these points. A wider spacing between contours in a certain area of the deck indicates a low spot; a closer spacing a high spot. Adjacent high and low spots reveal a relatively bumpy region.

The extensive cracks of the deck on the Rte. 64 bridge were mapped from photographs taken from above the deck. To help define the cracks so that they could be readily identified in the photographs, two procedures were used. The first involved wetting the deck down with water. As the water evaporated it remained in the cracks longer than on the surface, and thereby clearly defined the cracks for a period of time that varied with the prevailing ambient conditions. This procedure did not prove to be entirely satisfactory since the water in some of the cracks evaporated before the photography could be initiated and completed. The second procedure involved chalking the cracks so they could be readily seen in the photographs. This procedure worked well, as two people could mark the cracks well ahead of the photographing so that there was no delay. Considerable effort and additional manual labor, however, are required to mark the cracks. Figure 12 is a plan view of the network of the cracking that can be shown by close-range terrestrial photogrammetry. On this particular deck the total lengths of the cracks measured 2,625 ft. Of this total, 1,344 ft were cracks measuring less than 1 mm in width. While this kind of mapping would not ordinarily be done on a bridge deck, the results show that close-range photogrammetry can be used to conduct extremely intricate surveys.

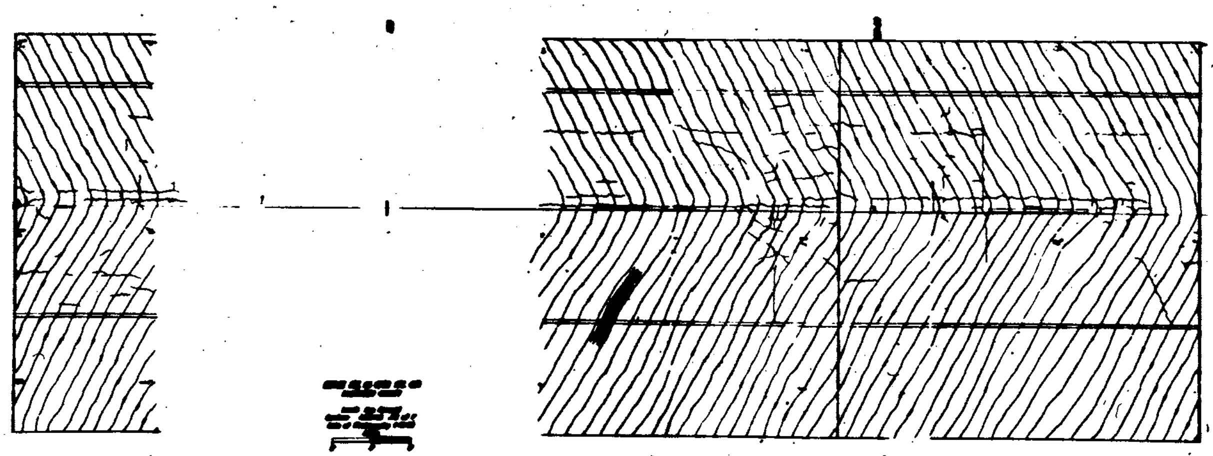

Figure 11. Contours spaced at 0.05-ft intervals reveal deck surface irregularities.

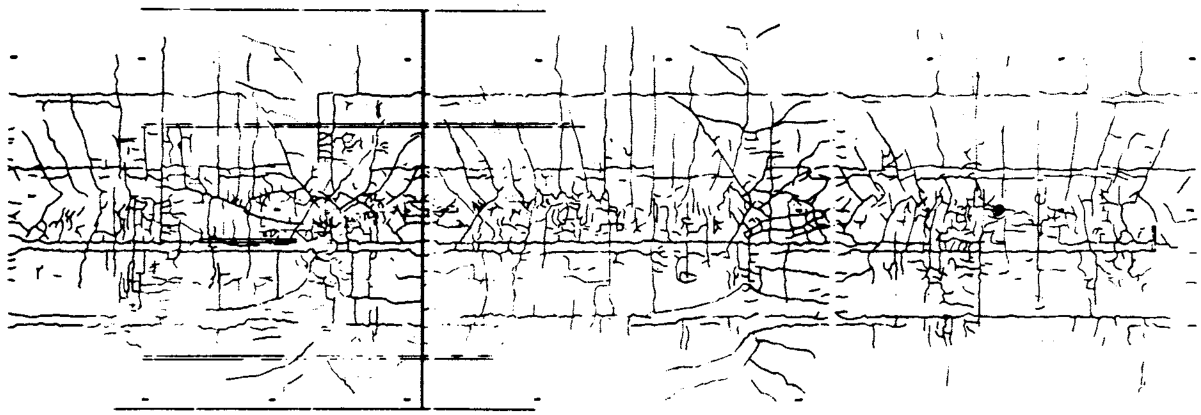

Figure 12. Plan view of cracks in deck of Rte. 64 bridge over Rte. 639.

Deflection of Bridges

To evaluate the applicability of close-range terrestrial photogrammetry for measuring small structural movements, two bridges were studied. Both bridges were under construction at the time and could be photographed prior to and subsequent to the placement of the concrete deck on the steel girders. Thus, the dead load deflection of the steel girders under the weight of the concrete deck could be measured. The first of the two bridges was the Rte. 66 Metro bridge over Rte. 495 in Fairfax County; the second was the 5th Street (alternate Rte. 29) crossing of the Norfolk and Western and Southern railroads in Lynchburg. Each of these bridges has at least one span over open land that could be used to position the camera under the structure. Thus, as opposed to the use of the camera above the structure, as described earlier, the camera was used beneath the structure, with photographs being taken of the underside of the bridge superstructure.

Metro Bridge over Rte. 495

The Rte. 495 bridge is composed of 11 simply supported spans. Deflection measurements were taken on span 7, which is 107 ft long between bearing points and, like all the remaining spans, is composed of two steel box girders. The two vertical webs of each box are connected at the bottom by a steel plate, but each web has a top flange similar to that of a regular plate girder. The deck for the bridge, in effect, completes the box section. The rails for the inbound and outbound Metro tracks are centered over each box girder.

Three camera positions, located transverse to the bridge, were established on the ground beneath span 7 such that its maximum mid-span deflection could be measured. The camera positions were approximately 21 ft below the bottom of the box girders. Near mid-span, 12 paper targets were glued to the bottom steel plates of the box girders. From each of the camera positions, overlapping photographs were taken to create the stereo pairs. A typical photograph taken from the center position beneath the structure is shown in Figure 13. As can be noted from the photograph, the wood forming for the deck concrete is in place.

A triangulation approach was used to establish the horizontal and vertical positions of the targets on the structure. From each end of a 65-ft baseline located on the ground, both horizontal and vertical angles were turned to the targets. Two elevations for each of the targets were calculated -- one from each end of the baseline. Good agreement between these elevations indicated that the control for the close-range photogrammetry was adequate. In making the subsequent deflection measurements, a triangulation program was used rather than setting the photographic models in a stereoplotter. The measurements were made from the original glass plates using a Mann 422F mono-comparator, and the digitizer located the principal point and rotated the coordinates. In the analysis, the target positions established from the ground measurements were assumed to be fixed and the perspective center was assumed to move. The reverse is actually true, but the vertical movement of the structure can be determined in this manner since the displacement of the bridge can be computed from an apparent movement of the perspective center.

In the field, the elevation of the camera base was determined by differential leveling. By adding to this elevation the distance to the perspective center, the true elevations of the perspective centers at the three camera stations were determined. From the analytical triangulation program, the apparent elevation of the perspective center was calculated for each of the camera positions. The difference between the true and the apparent elevations of the perspective center at each camera position gave the amount of movement of the bridge resulting from the load to which the girders were subjected.

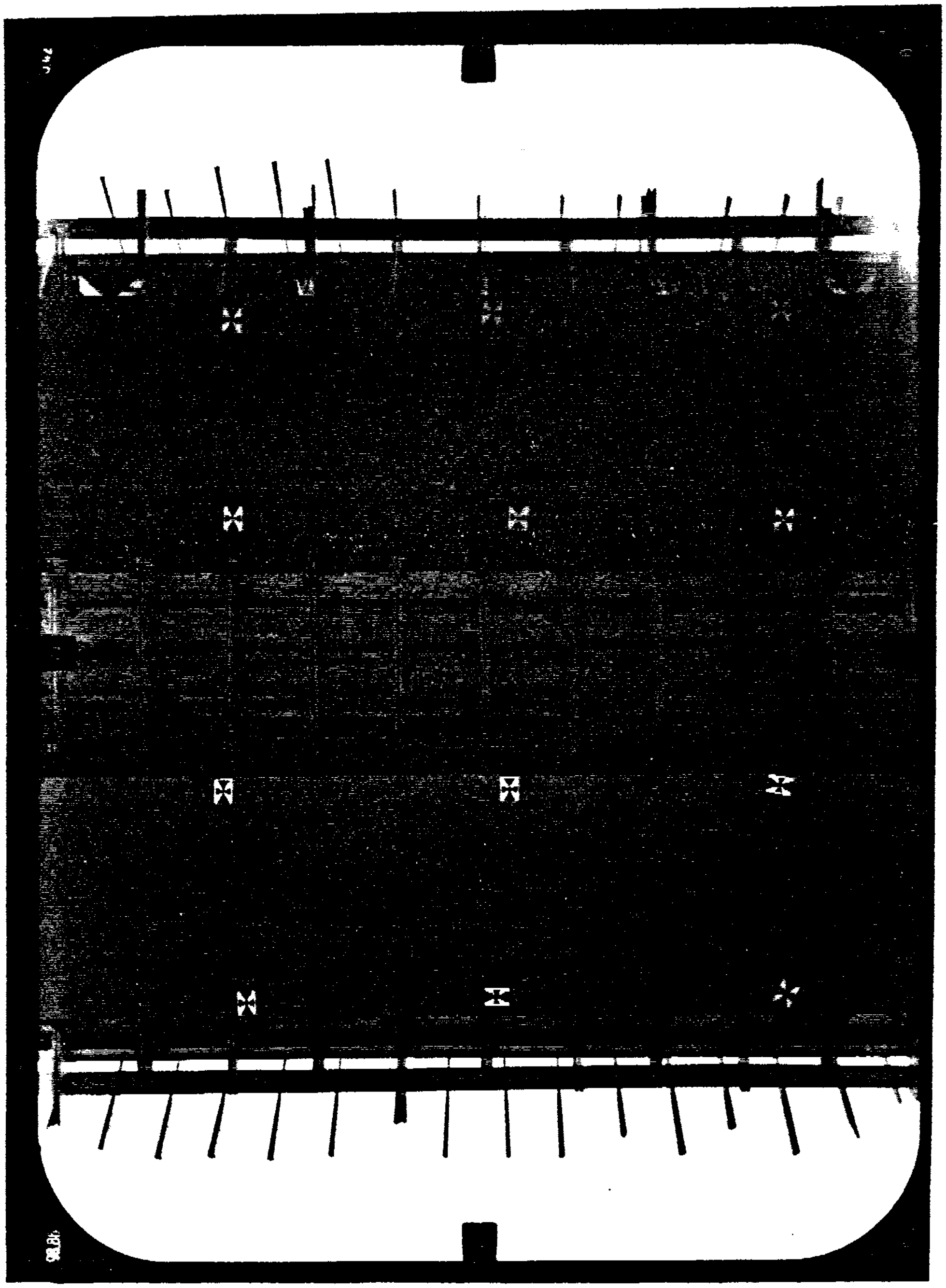

Figure 13. Underside of span 7 of Rte. 66 Metro box girder bridge prior to deck placement. Twelve targets for the photogrammetry are shown.

The photography was conducted during the summer, when solar radiation can cause substantial differential temperatures in steel girder bridges. The results of other studies have shown that steel girders will deflect upward during the day when the top flanges are hotter than the lower.(8,9) Since one of the objectives of this study was to evaluate the use of close-range photogrammetry for measuring small structural movements, the span was photographed at several times under the unloaded condition, i.e. before the deck was placed, to measure the thermally induced deflection.

All of the photographs of the bridge were taken over an eight-day period during the latter part of June. During this period, photographs were taken at three times before the deck was placed and at two times afterwards. The initial three sets of data were taken over a two-day period to provide a reference and a measurement of the thermally induced deflection occurring over a period of several hours. The last two sets of data were recorded during a single day (after the concrete deck had been placed), and were used to measure the dead load deflection of the span. The last of these two sets of photographs were taken at approximately the same time of day as the initial data to ensure that the environmental conditions would be reasonably the same.

The measurements obtained are given in Tables 3 and 4. Table 3 gives the deflection measurements taken from each camera station, and these are listed with reference to the initial photographs taken on June 23. Points A, B and C were the three camera positions on the ground beneath the span. Point B was the center camera position and points A and C were located approximately 7 ft to either side. Table 4 shows the deflection of the span occurring between photography times.

The measurements indicate that between 2:00 p.m. on June 23 and 8:10 a.m. the next morning, the span deflected downward at mid-span by an average of 0.011 ft (Table 4). This result appears to be in order, since the span would have been expected to be higher at 2:00 p.m. due to the thermally induced moment. By 8:10 a.m. the next morning (June 24), the top flanges would, of course, be cooler and the girders would deflect downward with respect to their position at 2:00 p.m. of the previous afternoon. Between 8:10 a.m. and 10:08 a.m., differential temperatures between the upper and lower flanges would develop as the top flanges began to heat, and would cause the girders to deflect upward. As shown in Table 4, the measurements indicate that the girders deflected upward an average of 0.016 ft. These results strongly suggest that the technique is capable of showing not only the correct direction of small structural movements, but their order of magnitude as well.

The next two series of measurements shown in Table 4 are the mid-span deflections of the span resulting from the weight of the concrete deck. Between 10:08 a.m. on June 24 and 10:40 a.m. on June 30, the average mid-span deflection was 0.252 ft. Between 10:40 a.m. and 2:22 p.m. on June 30, however, the span deflected upward by 0.011 ft to yield a final average deflection of 0.236 ft (Table 3), or about 2 13/16 in. This upward deflection once again indicates a differential temperature effect, with the top flanges being warmer than the lower.

The calculated plan value for the deflection of the steel girders under the weight of the concrete was given as 2 1/16 in. While there is a 3/4-in difference between the plan and measured values, it cannot be assumed that the photogrammetric results are in error. Slight variations in the dimensions of the steel or concrete could explain some of the difference. The photogrammetric measurements developed from each of the three camera positions are reasonably consistent, showing differences on the order of 1/8 in or less for all measurements but one -- which differed by less than 1/4 in. Some of this difference could be attributed to small thermal movements in the bridge occurring during the timed required to move the camera from one position to another.

Table 3

Photogrammetric Deflection Measurements at Mid-span (Span 7, Rte. 66 Metro Bridge over Rte. 495)

Date	Time	Condition	Relative Deflection, Ft* Point A	Point B	Point C	Average
6-23	2:00 p.m.	Unloaded	Reference	Reference	Reference	-----
6-24	8:10 a.m.	Unloaded	- 0.018	- 0.001	- 0.015	- 0.011
6-24	10:08 a.m.	Unloaded	- 0.001	+ 0.014	+ 0.002	+ 0.005
6-30	10:40 a.m.	Loaded	- 0.259	- 0.239	- 0.242	- 0.247
6-30	2:22 p.m.	Loaded	- 0.246	- 0.230	- 0.232	- 0.236

* - = Downward deflection with respect to the reference measurement
\+ = Upward deflection with respect to the reference measurement

Table 4

Mid-span Deflection Occurring Between Photography Times (Span 7, Rte. 66 Metro Bridge over Rte. 495)

Time Period	Deflection, Ft* Point A	Point B	Point C	Average
2:00 p.m. 6/23 - 8:10 a.m. 6/24	- 0.018	- 0.001	- 0.0015	- 0.011
8:10 a.m. 6/24 - 10:08 a.m. 6/24	+ 0.017	+ 0.015	+ 0.017	+ 0.016
10:08 a.m. 6/24 -10:40 a.m. 6/30	- 0.258	- 0.253	- 0.244	- 0.252
10:40 a.m. 6/30 - 2:22 p.m. 6/30	+ 0.013	+ 0.009	+ 0.010	+ 0.011

* - = Downward deflection
\+ = Upward deflection

5th Street Bridge over N & W and Southern Railroads

The 5th Street bridge is of a three-span, continuous steel plate girder design. Since it was under construction during the study, it provided an opportunity to use close-range photogrammetry to measure the deflection of girders resulting from the weight of a concrete deck.

The two end spans of the 5th Street bridge are 147 ft long and the center span is 170 ft long. Because the bridge is of a continuous design, the deflection of the steel girders of any span is influenced by the loading on any other span; therefore the 5th Street bridge is unlike the simple span Metro bridge discussed earlier. Due to the availability of open land beneath the bridge, the 170 ft center span, shown in Figure 14, was targeted for study. Figure 15 shows the targets being placed on the underside of the span, which is composed of five haunched steel girders.

The procedures used for the photogrammetric measurements taken on this bridge were similar to those used on the Metro bridge. Three rows of targets were applied to the girders at right angles to the centerline and near the middle portion of the span. As before, three camera positions were established on the ground beneath the center row of targets and at right angles to the bridge. Elevations were determined on the girders at all the target points and at mid-span. In addition to the photogrammetric measurements, an engineer's level was used to take elevations at all the target points both before and after the girders were loaded with the concrete deck as a check on the photogrammetric measurements. All of the photographs and elevation measurements were taken on two occasions; one in September before the deck was placed and another in April of the following year after the deck was completed. Finally, the before and after elevation measurements were used to calculate the deflection of the steel girders at each of the target points. Since the bridge is skewed at 27° but the targets are placed at right angles to the bridge, additional deflection measurements at mid-span were taken from the photographs.

A comparison of the deflection measurements taken by leveling with those from photogrammetry is presented in Table 5. The deflections at the 15 targets are listed according to row and numbered from 1 to 5 from the east to the west side of the span. The measured deflection of each point as determined by photogrammetry and that by leveling are given along with the difference between the two. For 7 of the 15 points there was no difference between the two measurements. Five of the 15 differed by 0.01 ft, one by 0.02 ft and two by 0.03 ft. Therefore, 12 of the 15 points differed by no more than 0.01 ft, or about 1/8 in. The average difference between the two techniques was less than 0.01 ft.

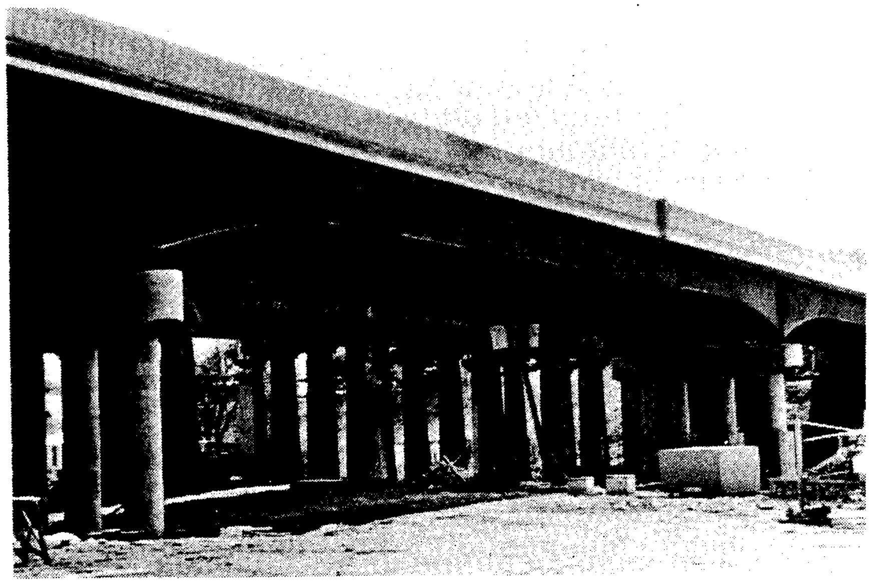

Figure 14. View of the center span of the three-span, continuous steel girder 5th Street bridge.

Figure 15. Targets being placed on the center span of 5th Street bridge.

The deflection at mid-span of each girder as determined from the photographs is given in Table 6. As can be noted, a slight upward deflection was measured which did not agree with the 0.07 ft downward deflection provided on the bridge plans. The average values from either Table 5 or Table 6 suggest that very little mid-span deflection resulted from the placement of the concrete deck. Upon investigation, it was found that for the calculation of deflections for continuous span bridges it is assumed that the concrete is placed on the entire bridge at once. However, the bridge was not constructed in this manner. The concrete was placed in the positive moment areas of the two end spans first; at a later date, it was placed in the positive moment region of the center span, and still later, in the negative moment regions over the piers. The actual situation was entirely different from that of assuming that all the deck concrete on the structure was plastic at one time. When concrete is placed on the two end spans, for example, the center span will deflect upward. After the concrete sets on the end spans the moment of inertia increases due to composite action with the steel. This increased the resistance to downward deflection of the center span when the concrete deck was placed on its position moment region. Thus, the weight of the concrete placed subsequent to the initial placement may have deflected the center span girders only back to their approximate unloaded position. Consequently, the deflection data obtained by photogrammetric means and checked by leveling are very likely accurate measures of what actually occurred. It is interesting to note that the assumption upon which the plan deflection calculations were based was not known to the photogrammetric engineer when the photogrammetric and leveling measurements were made.

Table 5

Comparison of the Deflections Measured by the Photogrammetric Technique with those Obtained Using an Engineer's Level (Span 2, 5th Street Bridge, Lynchburg, Virginia)

	Measured Deflection, Ft*		
Target No.	Photogrammetry	Leveling	Difference
A-1	0.00	- 0.02	0.02
A-2	+ 0.02	+ 0.01	0.01
A-3	+ 0.02	+ 0.02	0
A-4	+ 0.02	+ 0.03	0.01
A-5	- 0.02	+ 0.01	0.03
B-1	- 0.03	- 0.03	0
B-2	- 0.01	- 0.01	0
B-3	+ 0.02	+ 0.01	0.01
B-4	0.00	+ 0.01	0.01
B-5	0.00	0.00	0
C-1	+ 0.01	- 0.02	0.03
C-2	- 0.01	- 0.01	0
C-3	0.00	0.00	0
C-4	- 0.01	- 0.01	0
C-5	- 0.03	- 0.02	0.01
Average	-0.001	-0.002	0.009

* - = Downward deflection
  + = Upward deflection

Table 6

Photogrammetric Deflection Measurements at Mid-Span
(Span 2, 5th Street Bridge, Lynchburg, Virginia)

Girder Number	Deflection, Ft
1	+ 0.002
2	+ 0.015
3	+ 0.024
4	+ 0.005
5	0.00
Average	+ 0.009

CONCLUSIONS

The following conclusions can be drawn from this study of close-range terrestrial photogrammetry as applied to measurements of highway bridges.

1. Over the last 50 or 60 years, developments in photogrammetry have been mainly in aerial photography and stereoplotting. During the last few years, however, close-range terrestrial photogrammetry has been rediscovered and is being used for various applications in a wide range of disciplines. Some recent applications to highway bridges have demonstrated the ability of this technique to meet otherwise difficult measurement and evaluation requirements at lower cost, using less time, and causing less disruption to traffic than would be the case with many other methods.

2. The results of the study show that close-range terrestrial photogrammetry can be used for the measurement of small order of magnitude structural displacements and differences in elevation. The measurements of the deflection of steel girders under concrete loading suggest that accuracies on the order of 1/8 in can be achieved with normal care using the UMK 10/1318 camera that was utilized in the field study. The technique could thus be used to indirectly determine the general order of magnitude of loads

imposed upon structural members whenever their deflections can be measured.

3. The UMK 10/1318 camera gave satisfactory results for the measurements taken during the study. Accuracies were within the desirable range for the types of measurements being taken. This camera was preferred over some others because of its large, 5 in x 7 in, format. Consequently, it could be used at distances closer to the object and required fewer photographs than cameras having smaller formats.

4. Close-range photogrammetry can be useful on bridge deck condition surveys by eliminating the need for field sketches and by reducing the amount of field measurements required. In addition, the photographs can be used to obtain additional information if needed or be used as a reference to gauge potential future changes in condition, elevation, or relative position. These advantages might be the primary reason for using close-range photogrammetry for a bridge deck condition survey, since the savings in field work and manpower is offset by the need for photogrammetry personnel and a lift bucket truck and operator.

5. Measurements of small differences in elevation, such as those associated with bridge deck surface irregularities, can be accomplished to accuracies within 1/8 in using normal care. Greater accuracies could probably be obtained if necessary. Surface irregularities can also be shown by developing close-interval contours from the photographs.

6. Extremely intricate bridge deck condition surveys, such as the mapping of cracks, can be accomplished with close-range photogrammetry. While this type of survey would not ordinarily be conducted, in this study it did serve to demonstrate some of the capabilities of the technique.

RECOMMENDATIONS

Based on the results of the work by Spero, the preliminary results of this study, and the opinion of the photogrammetric engineer, it was recommended that the Virginia Department of Highways & Transportation purchase the UMK 10/1318 camera used in the study. Subsequently, the camera was purchased, giving the Department the capability of making use of close-range terrestrial photogrammetry when the need arises in the transportation field as well as in other disciplines. Recently, an analytical stereoplotter was purchased, which adds to the Department's photogrammetric capabilities. Close-range terrestrial photogrammetry offers an approach to solving difficult measurement problems that might be associated with bridge maintenance, repair, and rehabilitation. It is recommended that highway and bridge engineers be made aware of the availability and capability of this technique.

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