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Monitoring a Gabion Wall by Inclinometer and Photogrammetry

A combination of the two methods was found to be best.

Abstract: *There are a number of methods which may be used to monitor structural deformations. The comparison and analysis of two are discussed. A photogrammetric system is employed as an external method and an inclinometer system is used as an internal method. The general flow of data for the photogrammetric system along with the principle and use of an inclinometer are described. The comparison and analysis are possible in several ways; however, the general conclusion is that the best monitoring system is a combination of the two methods.*

Introduction

The importance of obtaining the dimensional changes of any structure during and after the construction is well known to engineers. There are a number of methods and instruments to accomplish this. Some instruments, such as inclinometers, extensometers, etc., are built into the structures, thus providing information about their internal changes and conditions. Other monitoring methods, such as photogrammetry, are surface-monitoring methods providing three-dimensional information about external deformation.

It is of interest to compare external and internal systems. This opportunity was provided by the fact that the Washington State Department of Transportation is currently constructing the final segment of I-90 in the Snoqualmie Pass area. The eastbound roadway will utilize the existing highway while the westbound roadway is being built on a new line and grade on the opposite side of the valley. Several large gabion walls were constructed along the roadway and in some areas to support the roadway. The largest wall is approximately 1,200 feet long and 51 feet high at its highest point. This wall was instrumented internally with an inclinometer. The photogrammetric method, i.e., external monitoring, was reported upon to the American Society of Photogrammetry by Veress and Sun (1978).

PHOTOGRAMMETRIC METHOD

The photogrammetric project was sponsored by the State of Washington Department of Transportation in cooperation with the Federal Highway Administration. The research was conducted at the University of Washington by S. A. Veress who is the principal investigator of the project.

The planning started in 1975 and is described by Flint (1975). A modified KA-2, 24 in. focal length camera was used in terrestrial mode. The final design and modifications of the project were executed and completed by Sun (1976), and it has been in operation since September 1976.

A flow diagram is given by Figure 1 and is discussed in detail by Flint (1975), Sinco, Slope Indicator Company (no date), Veress *et al.* (1977), and Veress and Sun (1978). The general layout of the photogrammetric project is shown by Figure 2.

A bird's-eye view of the construction site is shown by Figure 3. The structure is located on the west side of the valley and the camera stations were placed on the east side at about 3,000 feet (1 km) from the wall.

The plan was to cover the entire structure so that each of the photogrammetric targets would be visible in three different photographs. This was accomplished from three camera stations. The number-2 camera station (CS2) was chosen so that it was rotatable in two directions. This geometry provides a parallactic angle (i.e., approximately the intersecting angle on the structure from CS1 and CS3) of about 60°. These camera stations are established on concrete foundations so that they are considered to be "fixed" positions. The frontal nodal point of the camera was determined at each station by the ground survey methods described by Sun (1976) and Veress and Sun (1978).

The basic concept in designing this system (fixed camera position) is economy. However, it imposes a considerable limitation on achievable accuracy. If the camera is located in stable solid bedrock some distance from the roadway, such as CS3, the obtained accuracy is sufficient. However, if the station is close to a roadway as is CS1, the bedrock is subjected to vibration due to heavy truck traffic. Thus, small movements of the station must be considered. Rotatable bases such as CS2 are not recommended because the "fixed camera position" considered in the computation cannot be maintained in practice.

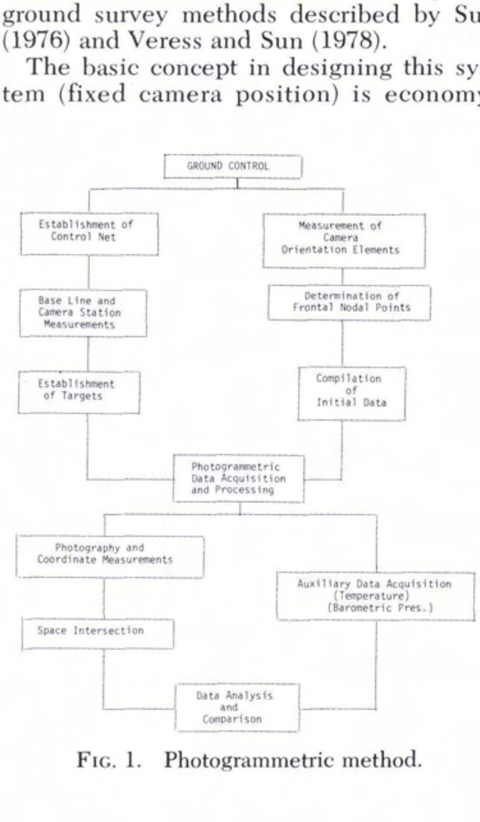


FIG. 1. Photogrammetric method.

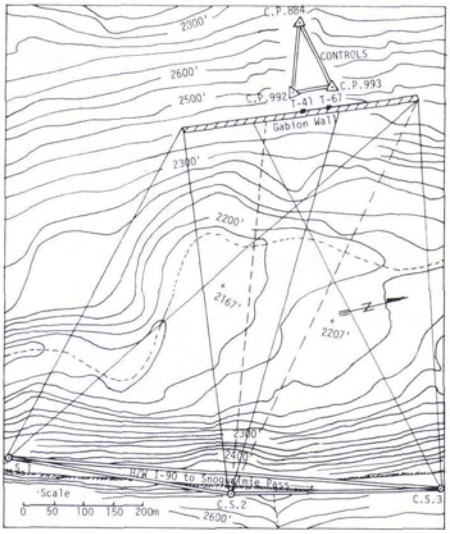


FIG. 2. General design of the photogrammetric project.

These disadvantages of the system have been partially corrected by modifying the camera mounts and numerically checking by placing photogrammetrically determined control targets on solid bedrock above the wall. These targets serve a dual purpose; to check the camera position and to give information about the accuracy achieved. (The

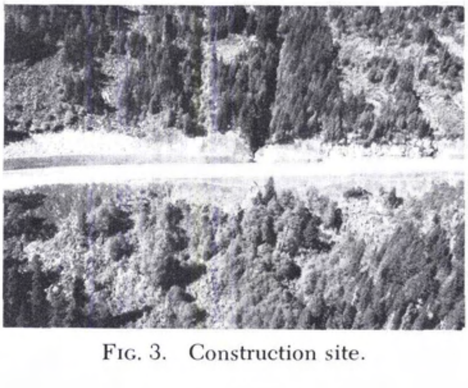


FIG. 3. Construction site.

locations of these targets are shown in Figure 2 as C. P. 884, 992, and 993.)

Targets were placed on the gabion wall and their *XYZ* coordinates were determined at each monitoring time. An array of targets shown by Figure 4 are located near the inclinometer station. The details of the targets are shown by Figure 5.

The methods of data acquisition and refinement are given in Sun (1976), Veress *et al.* (1977), and Veress and Sun (1978). The data processing has been made routine by utilizing two computer programs. The photo-coordinates, measured on a comparator (the AP/C analytical plotter at the University of Washington), were the input for the first program. An affine transformation was performed in order to provide picture coordinates, correction for autocollimation point, the orientation matrix, and finally the *XYZ* coordinates of target points.

The second program tabulates the results accumulated for each control point beginning at "zero" date (at the start of monitoring). Table 1 represents the output of the first and second program. In Table 1 the *X* axis coincides with the longitudinal axis of the wall while the *Y* axis is vertical. The Z axis is perpendicular to the wall; thus, it represents the structural deflection.

The time required for data acquisition is about 50 minutes. About five hours are required from the comparator measurement to obtain the final results. The photographic developing and processing time depends upon the priority of work as well as preparation of fresh chemicals, etc. It can be concluded that this is a rapid monitoring method, realizing that the above time was required for 100 target points.

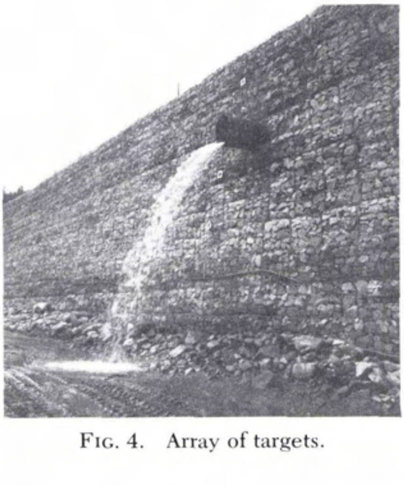


FIG. 4. Array of targets.

It may further be mentioned that photogrammetric methods have the following advantages:

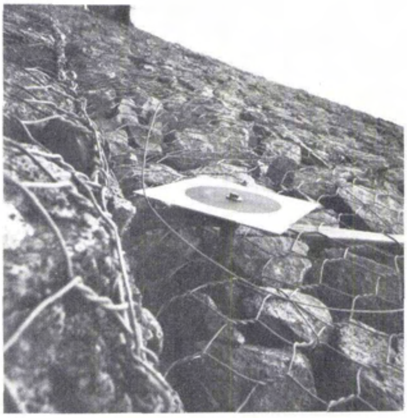


FIG. 5. Details of the target.

- Independence from the structure.
- Three-dimensional information.
- Independence from most photogrammetric systematic errors because the camera always occupies the same position.
- Enconomically, it only requires two men to operate the whole system. The economy of the method cannot be simply measured by man-hours because the general preparation and data processing is nearly the same for either small or large projects. The photogrammetric method is a mass production system and, therefore, most economical for a large project monitoring a large number of points. For small projects it should not be considered.
- Finally, it must be remembered that it provides information only about the surface of the structure.

INCLINOMETER METHOD

An inclinometer casing was installed by the Washington State Department of Transportation at two locations in the gabion wall. These locations were chosen considering the normal height with the most uniform backfill conditions for all internal instrumentation. Both of these locations have photogrammetric targets on their surfaces (the 40 and 60 series). This provides the basis for comparison between external and internal monitoring. The photograph on Figure 6 shows the installation of the two inclinometer casings during construction.

A detailed description of the inclinometer method is given in Sinco, Slope Indicator Company (no date). Therefore, only a brief description has been given here to highlight the principle and show the data acquisition of an internal monitoring system. The inclinometer system consists of four units: the

TABLE 1. OUTPUTS OF THE FIRST AND SECOND PROGRAM

SPACE INTERSECTION RESULTS USING THREE CAMERAS

			X	*Y*	Z
POINT 1	7 JUL	992	1429.626000	1029.340000	1647.646000
POINT 2	7 JUL	993	1495.512000	1026.655000	1660.281000
POINT 3	7 JUL	884	1432.491000	1096.625000	1762.655000
POINT 4	7 JUL	016	1443.156166	1003.824057	1601.781974
POINT 5	7 JUL	041	1458.089886	1004.487404	1605.135452
POINT 6	7 JUL	042	1458.053012	1002.609374	1604.716275

GABION WALL MONITORING RESULTS USING ARTIFICIAL TARGETS

DATE	POINT	*X*(m)	*DX*(cm)	*Y*(m)	*DY*(cm)	Z(m)	*DZ*(cm)	CAMERAS
7 SEP	041	1458.090	0.0	1004.563	0.0	1605.204	0.0	124
12 OCT	041	1458.097	−0.7	1004.557	0.6	1605.170	3.4	124
18 OCT	041	1458.088	0.2	1004.538	2.5	1605.179	2.4	124
27 OCT	041	1458.100	−1.0	1004.530	3.3	1605.172	3.2	124
3 NOV	041	1458.100	−1.0	1004.533	3.0	1605.149	5.5	124
23 NOV	041	1458.105	−1.5	1004.536	2.7	1605.158	4.6	124
1 DEC	041	1458.106	−1.6	1004.519	4.4	1605.136	6.7	124
28 JAN	041	1458.117	−2.7	1004.610	−4.7	1605.237	−3.3	12
12 APR	041	1458.098	−0.8	1004.526	3.7	1605.156	4.7	124
26 MAY	041	1458.102	−1.2	1004.515	4.8	1605.146	5.8	124
10 JUN	041	1458.089	0.1	1004.490	7.3	1605.152	5.1	12
6 OCT	041	1458.091	−0.1	1004.501	6.2	1605.151	5.3	124
25 APR	041	1458.088	0.2	1004.503	6.0	1605.158	4.6	124
7 JUL	041	1458.090	0.0	1004.487	7.6	1605.135	6.8	124

moveable borehole sensor; the portable, digital indicator; the interconnecting electrical cable; and the inclinometer guide casing installed permanently in the structure to be surveyed.

The inclinometer has the capability of measuring the deflection of the casing with an accuracy of ±2.5 mm per 10 m of casing. The casing, considered to be fixed, is permanently imbedded in the foundation of the structure and as such has no horizontal movement. The inclinometer casing follows only the movement of the body of the structure. The inclinometer casing is circular in cross section and has two pairs of grooves located perpendicular to each other as shown in Figure 7. A pair of these grooves or guides is located in such a manner that it is perpendicular to the face of the structure. Thus, the inclinometer measures the deflection of the structure (corresponding to Z direction of the photogrammetric method). The second pair of guides is oriented in the longitudinal direction of the structure. This is the longitudinal direction of the gabion wall and it corresponds to the *X* direction of

FIG. 6. Installation of inclinometer.

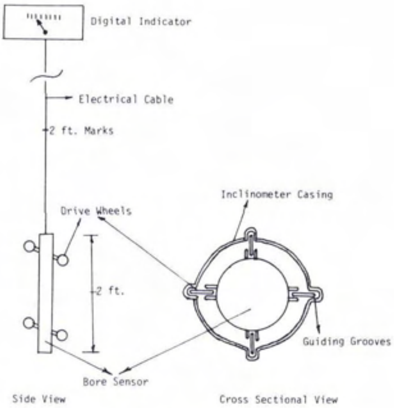


FIG. 7. Outline of the inclinometer.

the photogrammetric method. The movement in the Y direction (settlement) is monitored by measuring the length of the casing.

Inclinometer measurements are obtained by lowering the sensor, which is supported by the electrical cable, into the casing. Alignment of the probe is maintained by the wheels of the sensor traveling in the casing grooves. The cable is marked at one-foot intervals so that the position of the sensor can be measured in reference to the top of the casing (Figure 7).

In general, the data are acquired by lowering the sensor to the bottom of the casing, then withdrawing the sensor and taking measurements at convenient intervals. The distance between the wheels on the probe is two feet (the most common interval used). After taking slope readings at two-foot intervals from the bottom of the casing to the top, the sensor is rotated 180° and reinserted so that a second set of readings can be taken at the same position in the casing but in opposite directions. This doubling process helps eliminate or minimize errors contributed by casing irregularities, depth measurements, and sensor alignment geometry. Each reading gives the slope of the casing over the two-foot length measured in terms of 2 Sin θ_i, where θ_i is the angle between the axis of the sensor and true vertical (Figure 8).

The casing inclination may be computed using the algebraic "difference" between two readings at the same depth in opposite grooves, i.e.,

$$\Theta_i(\text{degrees}) = \sin^{-1}\left(\frac{\text{difference}}{4 \times 10^4}\right)$$

Note: The system reads to 0.0001; however, in recording the data the value is multiplied by 10^4; thus, there is a 10^4 correction.

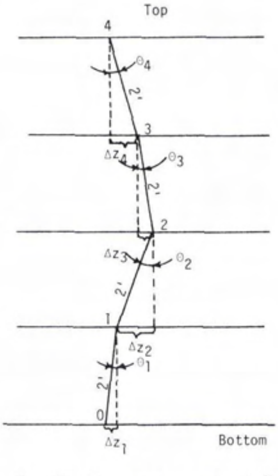


FIG. 8. Inclinometer principle.

The lateral deflection of the casing over each unique two-foot segment measured can be computed as follows:

$$\begin{aligned} &\text{Deflection} \\ &\quad(\text{inches}) = \Delta Z_i = 24 \sin \Theta \\ &\text{or} \qquad \Delta Z_i = 24\left(\frac{\text{difference}}{4 \times 10^4}\right); \\ &\text{thus,} \qquad \Delta Z_i = 6 \times 10^{-4}\,(\text{difference}). \end{aligned}$$

The deflection Z_i at point i is given then as

$$Z_i = \sum_i^i \Delta Z_i$$

In this way, each time measurements are performed, the Z_i component for every i point can be computed. By subtracting the first reading, Z_{o_i}, the movement is determined as

$$DZ_{t_i} = Z_{t_i} - Z_{o_i}$$

where the suffix, t, corresponds to the time. The measurements were performed and compared to Z_{o_i}, which is the first measurement of the casing.

A sample readout with appropriate calculations is shown in Figure 9.

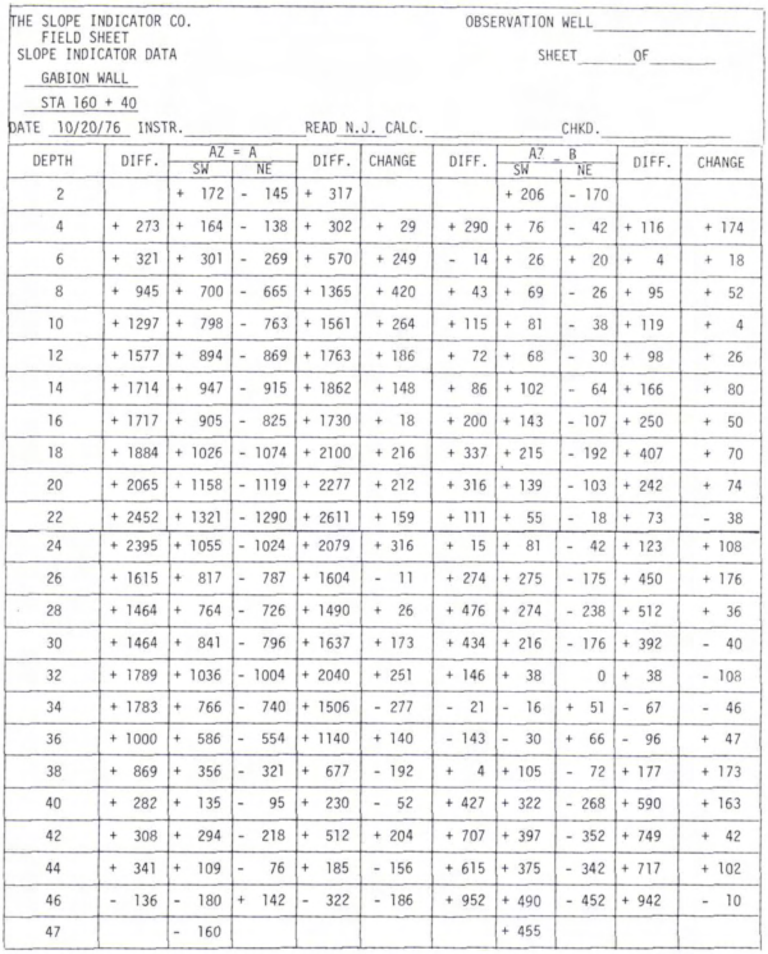
EVALUATION AND COMPARISON OF RESULTS

The gabion wall was photographed eleven times, which generated 3,300 measurements when considering the three coordinates of each of the hundred targets. This large amount of data is accompanied by measurements by the inclinometer (for an example, see Table 2). The construction engineer, therefore, must face the problem of finding a proper basis for the evaluation and comparison of the accuracies of these data. First, the measure of accuracies must be established.

There are several ways to solve this problem. One is to compare the coordinates of photogrammetrically established control points obtained at various times. Compute the standard errors from the deviations, assuming the control point fixed, and regard this as the measure of accuracy of the photogrammetric system. If one follows this method, it will be found that the standard errors of the coordinates are

$$\begin{aligned} \sigma_x &= \pm 24 \text{ mm} \\ \sigma_y &= \pm 23 \text{ mm} \\ \sigma_z &= \pm 35 \text{ mm} \end{aligned}$$

(σ_y represents a standard error in a settlement measurement and σ_z is the error in a



THE SLOPE INDICATOR CO.
FIELD SHEET
SLOPE INDICATOR DATA
GABION WALL
STA 160 + 40
DATE 10/20/76 INSTR. ______ READ N.J. CALC. ______ CHKD. ______

OBSERVATION WELL ______
SHEET ____ OF ____

DEPTH	DIFF.	AZ = A		DIFF.	CHANGE	DIFF.	AZ = B		DIFF.	CHANGE
		SW	NE				SW	NE		
2		+ 172	- 145	+ 317			+ 206	- 170		
4	+ 273	+ 164	- 138	+ 302	+ 29	+ 290	+ 76	- 42	+ 116	+ 174
6	+ 321	+ 301	- 269	+ 570	+ 249	- 14	+ 26	+ 20	+ 4	+ 18
8	+ 945	+ 700	- 665	+ 1365	+ 420	+ 43	+ 69	- 26	+ 95	+ 52
10	+ 1297	+ 798	- 763	+ 1561	+ 264	+ 115	+ 81	- 38	+ 119	+ 4
12	+ 1577	+ 894	- 869	+ 1763	+ 186	+ 72	+ 68	- 30	+ 98	+ 26
14	+ 1714	+ 947	- 915	+ 1862	+ 148	+ 86	+ 102	- 64	+ 166	+ 80
16	+ 1717	+ 905	- 825	+ 1730	+ 18	+ 200	+ 143	- 107	+ 250	+ 50
18	+ 1884	+ 1026	- 1074	+ 2100	+ 216	+ 337	+ 215	- 192	+ 407	+ 70
20	+ 2065	+ 1158	- 1119	+ 2277	+ 212	+ 316	+ 139	- 103	+ 242	+ 74
22	+ 2452	+ 1321	- 1290	+ 2611	+ 159	+ 111	+ 55	- 18	+ 73	- 38
24	+ 2395	+ 1055	- 1024	+ 2079	+ 316	+ 15	+ 81	- 42	+ 123	+ 108
26	+ 1615	+ 817	- 787	+ 1604	- 11	+ 274	+ 275	- 175	+ 450	+ 176
28	+ 1464	+ 764	- 726	+ 1490	+ 26	+ 476	+ 274	- 238	+ 512	+ 36
30	+ 1464	+ 841	- 796	+ 1637	+ 173	+ 434	+ 216	- 176	+ 392	- 40
32	+ 1789	+ 1036	- 1004	+ 2040	+ 251	+ 146	+ 38	0	+ 38	- 108
34	+ 1783	+ 766	- 740	+ 1506	- 277	- 21	- 16	+ 51	- 67	- 46
36	+ 1000	+ 586	- 554	+ 1140	+ 140	- 143	- 30	+ 66	- 96	+ 47
38	+ 869	+ 356	- 321	+ 677	- 192	+ 4	+ 105	- 72	+ 177	+ 173
40	+ 282	+ 135	- 95	+ 230	- 52	+ 427	+ 322	- 268	+ 590	+ 163
42	+ 308	+ 294	- 218	+ 512	+ 204	+ 707	+ 397	- 352	+ 749	+ 42
44	+ 341	+ 109	- 76	+ 185	- 156	+ 615	+ 375	- 342	+ 717	+ 102
46	- 136	- 180	+ 142	- 322	- 186	+ 952	+ 490	- 452	+ 942	- 10
47		- 160					+ 455			

FIG. 9. A sample readout with appropriate calculations.

deflection measurement from a structural point of view.)

The question immediately arises: Is this evaluation based on too few points (only three in this case)? Can it correctly represent the accuracy of the system? The answer becomes further dubious if one realizes that these points are located hundreds of feet behind the gabion wall and the accuracy of the photogrammetric method decreases with distance.

Another form of this evaluation is to compute the standard errors of the coordinates of the targets each time they are determined. Use these standard errors and compute the standard errors of the coordinate differences (settlement, deflection, and longitudinal motion). This standard error represents the accuracy of the system. This is more acceptable from a theoretical point of view, but it adds an additional 3300 measurements to be evaluated by the construction engineer. This method now is under study.

Another method is to compare accuracies of photogrammetric and inclinometer measurements simultaneously by best-fitting curve. Ten artificial targets were selected on the surface of the wall. The evenly distributed targets were representative of the total wall surface. The differences between data obtained at various times of measurement were computed and a best fitting curve was obtained. The deviations represent photogrammetric accuracy (Veress *et al.*, 1977).

Deviations from the best fitting curve and estimated accuracy with this method are

$$\sigma_{\Delta x} = \pm 5.7 \text{ mm}$$
$$\sigma_{\Delta y} = \pm 8.1 \text{ mm}$$
$$\sigma_{\Delta z} = \pm 10.0 \text{ mm}$$

The same procedure can be used for inclinometer measurements. If the corresponding standard errors are computed, then the results of inclinometer measurements are

$$\sigma_{\Delta x_i} = 7.2 \text{ mm}$$
$$\sigma_{\Delta z_i} = 2.1 \text{ mm}$$

These standard errors indicate that a reliable comparison can be made. A graphical illustration of these data comparisons is shown by Figure 10 where the best fitting lines obtained by photogrammetry and by inclinometer are shown in the Z direction as a function of time. For this illustration, three points were selected. Point No. 44 is close to the foundation of the wall, as shown in Figure 10a for which the best results have been obtained. The maximum difference between the photogrammetric and inclinometer deflection is only 5.0 mm.

Figure 10b shows a comparison at another part of the wall. The maximum difference here is 7.5 mm, which is about average.

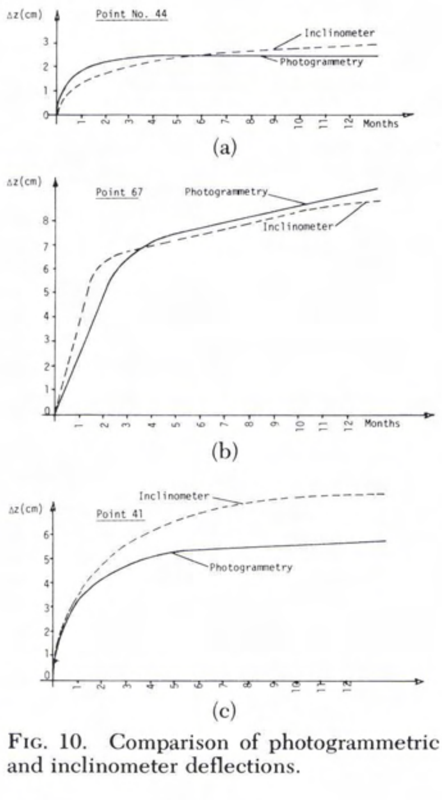
Figure 10c indicates the worst result, at point No. 41, which is located near the top of the 54-foot high wall. The maximum difference here is 21 mm.

It is of further interest to note that, during the monitoring of the wall, negative X (in the direction of the slope) motion was indicated by the photogrammetric method and later confirmed by inclinometer measurements. During photography, the elapsed time between the first and last photograph was about 45 to 50 minutes. The temperature change during this period, in some cases, was as much as 5° C (9° F). Therefore, this systematic "motion" was first considered as being caused by lateral atmospheric refraction. However, when it was compared to the daily temperature, a very poor correlation was found. On the other hand, when it was compared to the average temperature of a ten-day period previous to the monitoring time, the correlation was better in the X and Y direction (longitudinal motion and settlement) and there was no correlation in the Z direction.

Figure 11a shows the combined photogrammetric, inclinometer, and temperature variation as a function of time. Figure 11b shows the settling and the temperature variations as a function of time. This would indicate that the combined methods register the thermostatic expansion of the wall. The result is far too short to arrive at a meaningful conclusion other than a graphical illustration. It is indicated that this problem should be examined further to arrive at a quantitative solution to this question.

CONCLUSION

This study indicates that the combination of the two systems, i.e., the external and

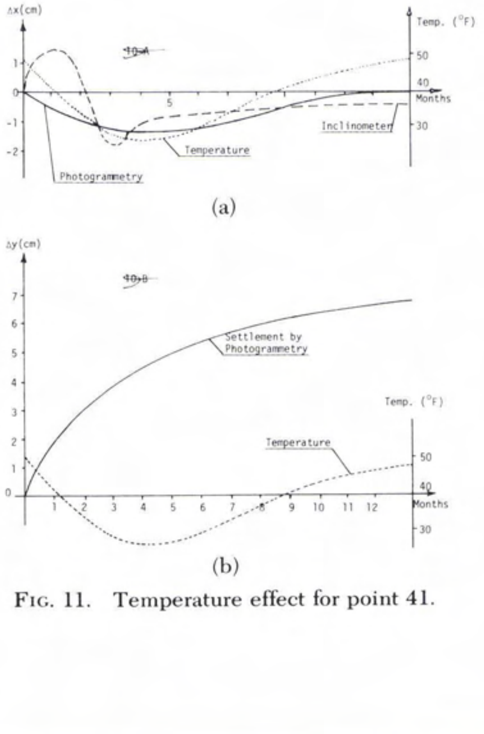


(a)

(b)

(c)

FIG. 10. Comparison of photogrammetric and inclinometer deflections.



(a)

(b)

FIG. 11. Temperature effect for point 41.

internal monitoring systems, would be an ideal tool to monitor large structures.

The comparison and simultaneous evaluation of the internal and external monitoring systems can be based effectively on an approximate but practical concept. This concept consists in using a best fitting curve and determining the deviations of points from that curve.

The combination of the two systems appears to provide a very effective research tool, particularly when the effect of additional variables, such as the temperature effect on a flexible structure, is investigated.

The disadvantage of this combined system is that it is employable only for new structures while the old ones should be monitored by surface methods.

The opinions, findings, and conclusions expressed in this publication are those of the authors and are not necessarily those of the Washington State Department of Transportation.

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