# Development of a measuring system for long-term structures' displacements

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# Development of a Measuring System for Long-Term Structures' Displacements

## Développement d'un système de mesure pour les déplacements structuraux à long terme

## Entwicklung eines Mess-Systems für Langzeit-Bauwerksverschiebungen

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**SUMMARY**

Displacement measuring system utilising a laser beam for large scale concrete structures has been developed. To apply this system for long-term monitoring, several improvements have been made. Based on the measured displacements of existing concrete structures, the long term behaviour of these concrete structures can be explained.

**RÉSUMÉ**

Un système de mesure des déplacements utilisant les rayons laser pour les grandes structures de béton a été développé récemment. Plusieurs améliorations ont été réalisées pour une application de ce système en vue d'une observation à long terme. Sur cette base, le comportement à long terme des structures en béton peut être expliqué.

**ZUSAMMENFASSUNG**

Ein mit Laserstrahlen arbeitendes Mess-System für Verschiebungen grosser Betonkonstruktionen wurde neu entwickelt. Um dieses System auch für Langzeitbeobachtungen nutzen zu können, wurden viele Verbesserungen gemacht. Basierend auf den gemessenen Verschiebungen von bestehenden Betonkonstruktionen kann das Langzeitverhalten dieser Betonkonstruktionen erklärt werden.

## 1. INTRODUCTION

The essential technique to monitor the varying states of existing large scale structures is obviously to measure the displacement of various points of a structure under the consideration to a degree which may be sufficient enough to judge its condition by the comparison either with the other similar structures or with the analytically estimated values. However, it is also too obvious that the long term observation of the displacement of the points in large structures is quite expensive and out of budgeting. It is rarely carried out in the present engineering except for a special case such as the seriousness of structure is to such an extent that an authority permits to allocate budget for it.

Therefore, it is desirable to develop a system which enables to measure the displacement of large structures with feasible cost for man power and for equipment. The present paper reports the successful development of a measuring system for long term displacement of a structure by the utilization of the laser beam and the opt sensitive displacement sensor attached to a structure. In developing the system, the most critical difficulty was the accurate resetting of laser launcher with same laser direction at the fixed launching location and accurate resetting of the opt sensitive displacement sensor in the same location of a structure.

## 2. FUNDAMENTAL CONCEPT OF THE SYSTEM

The concise and less laborious measurement of the displacement of a large scale structure requires the system of non contact type measuring system. What we have adopted is the utilization of the laser beam and the opt sensitive sensor (PSD sensor) which can measure the movement of laser focus with the resolution accuracy of 0.05 mm in the x and the y directions of which picture is shown in Fig.1. By combining two of these sensors, we can detect the movement of the point displacement in the three dimensional space statically as well as dynamically. The laser should be launched to the fixed direction every time during the measurement period of a year or even of 10 years for this specific purpose. The laser launcher and opt sensitive sensor should be removed after each measuring because those precision apparatus cannot be kept outside for a long period. Therefore in resetting of laser launcher we need accurate direction identifying apparatus. For this purpose, we adopted the theodolite. Its angle resolution capacity is 0.65 second in horizontal angle, and 1.0 second in vertical angle which means that the laser can be launched in the same direction within the maximum error of 0.315 mm at the distance of 100 m horizontally and 0.485 mm vertically, respectively. It can be said as the world most accurate angle identifying theodolite at present of which picture is shown in Fig.2.

However, besides this error we have several other errors which should be minimized. The resetting error of the launchers and sensors are the biggest factors in this sense. To minimize the error of resetting the launcher, the launcher post to which the launcher can be reset with $1 \times 10^{-4}$ mm error was invented and similarly to minimize the resetting error of PSD sensor, the PSD sensor table which can reincorporate the sensor in the same location with the accuracy of $1 \times 10^{-4}$ mm was also invented.

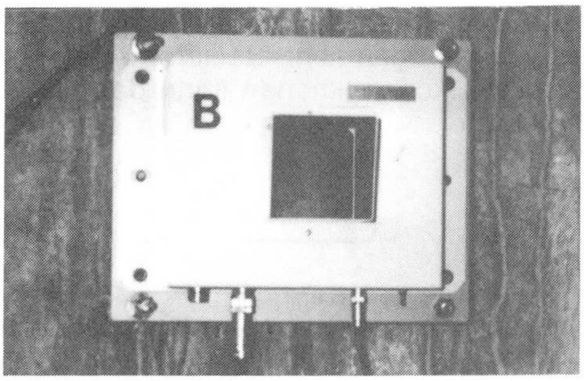



Fig.1 Opt sensitive sensor

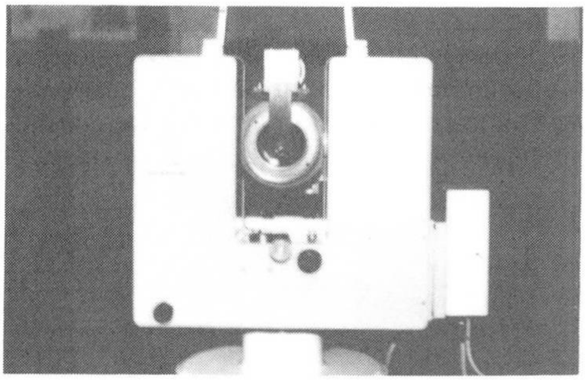


Fig.2 Precise theodolite

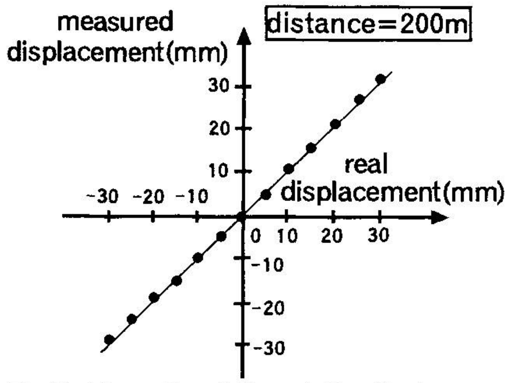



Fig.3 Linearity of the static displacement

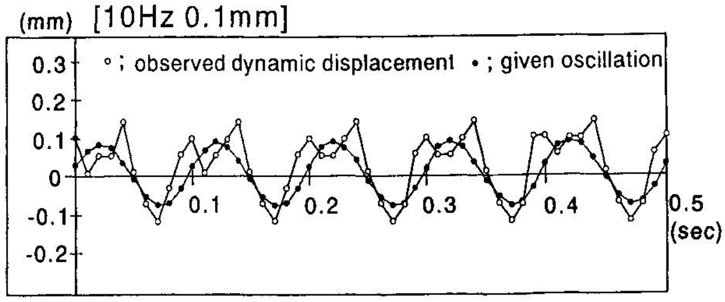



Fig.4 Linearity of the dynamic displacement

With all those precision apparatus, our strategy for the evaluation of the soundness of a structure is that during the life of a structure the measurement of the relative location in terms of the fixed three dimensional space which mark points are set with three unmovable points should be done. After certain elapse of time, the measurement has to be made. The time elapse depends on the maintenance circumstances. The measurement has to be continued as long as several years or more. Soundness judgment will be done with these observed data together with the analysis.

## 3. RELIABILITY OF THE DEVELOPED SYSTEM

Before discussing actual examples of application, the reliability of the system at present will be shown.

### 3.1 Linearity of the Static Displacement

The real displacement and measured displacement from the distance of 200 m are compared in Fig.3. It may be noted that good linearity is observed in both cases.

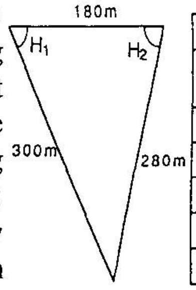
### 3.2 Linearity of the Dynamic Displacement

In Fig.4, the observed dynamic displacement of about 0.1 mm of about 10 Hz is shown in comparison with the given oscillation. Though there exists regularized difference, its accuracy is good enough for our purpose and more over it is satisfactory that the system has shown to be able to catch up the 10 Hz frequency displacement with this accuracy.

### 3.3 Reliability of resetting of the system

To identify the resetting accuracy, the three dimensional space coordinate identification was tried. After initial setting of the two launcher posts at about 180 m away, another fixed point is made about 300 m away from both the launcher posts making a triangle bench marks in the three dimensional space. Then, the horizontal angles of two corners were measured and apparatus were removed. After three weeks elapse, the resetting is done and the same two angles are measured.

In Table 1, the initial readings of the angles together with the following readings after resetting are shown. It may be noted that the agreement is quite satisfactory and the maximum resetting error is only 3 seconds which means that we can launch the laser with the accuracy at least of 1.5mm at the distance of 100 m even with the situation of resetting.




| Standard value: $H_1$=64° 58′ 55″ | | | Standard value: $H_2$=78° 48′ 27″ | | |
|---|---|---|---|---|---|
| Date | Measured Angle | Difference with $H_1$ | Date | Measured Angle | Difference with $H_2$ |
| 94/10/7 | 64° 58′ 52″ | -3″ | 94/10/6 | 78° 48′ 28″ | +1″ |
| 〃 | 64° 58′ 56″ | +1″ | 94/10/27 | 78° 48′ 29″ | +2″ |
| 〃 | 64° 58′ 57″ | +2″ | 〃 | 78° 48′ 28″ | +1″ |
| 〃 | 64° 58′ 57″ | +2″ | 〃 | 78° 48′ 30″ | +3″ |
| 94/10/27 | 64° 58′ 55″ | ±0″ | 94/10/28 | 78° 48′ 30″ | +3″ |

Table 1 Measured horizontal angles after resetting

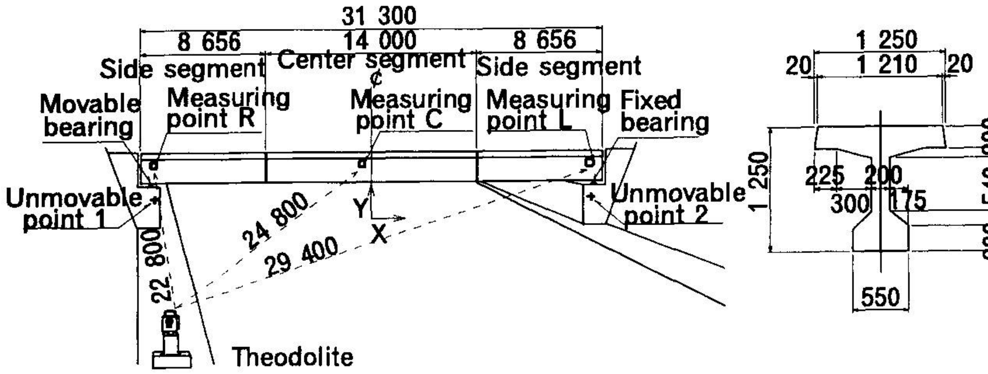



Fig. 5 General view of the bridge and the measuring points

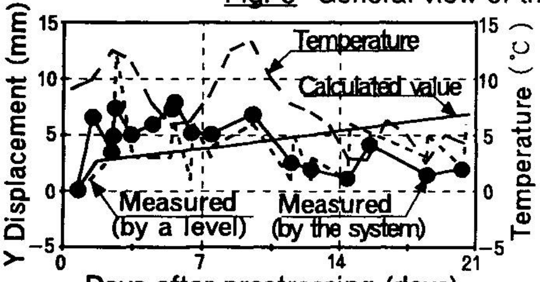



Fig.6 Measured and calculated vertical displacements of the point C

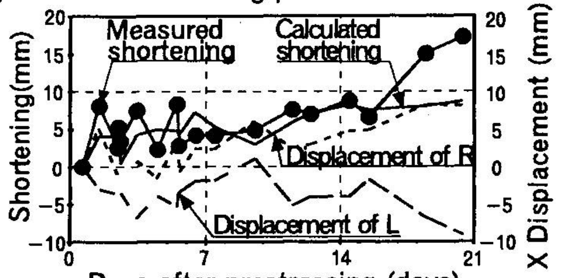



Fig.7 Shortening of the girder and measured X displacements of the points L and R

# 4. EXAMPLES OF APPLICATION

## 4.1 Prestressed Concrete Precast Segmental Girder Bridge

The displacement of existing prestressed concrete precast segmental girder bridge was measured. The bridge has seven main girders and each girder consists of three precast segments. The measurement was carried out for one of the girders from Nov. 10 when the prestress was introduced into the girder until Nov. 30, 1994. During the measurement, each girder is considred to deform independently. The general view of the bridge and the measuring points are shown in Fig.5.

The results of the measurements are shown in Figs.6 and 7. In these figures, the calculated values are obtained considering the influence of erection load, creep of concrete (due to prestressing force and dead load), shrinkage of concrete and loss of prestressing (due to creep, shrinkage and relaxation of prestressing steel). These influences are calculated numerically according to "Standard Specification for Design and Construction of Concrete Structures 1991" of JSCE. In addition, the calculated value in Fig.7 contains the deformation in the horizontal direction due to the temperature. In Figs.6 and 7, the indented shape of measured values is due to the daily temperature change.

In Fig.6, qualitatively similar behavior can be seen for the measured vertical displacement of the point C and for the calculated one. The displacement measured by a level indicates that the displacement measured by this system is reliable. It seems that the difference between measured and calculated values results from the loss of prestress in ungrouted tendons due to the sudden decrease in temperature and the difference in temperature between the upper flange and the web. In Fig.7, the measured shortening of the girder is presented. From Fig.7, the horizontal displacement of the girder can occur not only at movable bearing but also at fixed bearing when a rubber bearing is provided.

## 4.2 Prestressed Concrete Hollow Girder

The deflection due to daily temperature change, dead load and live load was measured for prestressed concrete hollow girder constructed in Narita Airport. The girder is 1.5 m high, 8.2 m wide and 35 m long. The cross section is shown in Fig.8. Fig.9 illustrates the measuring system in which one theodolite, two sensors and three unmovable points are used. The theodolite is installed about 90 m distant from the girder. The deflection of the bridge is obtained by the difference between the vertical displacement of the sensor A attached at the center and that of B at the support. Two unmovable points are allocated on abutments on both sides of the bridge and third one on another pier. Thermo-couples are embedded in a side surface of the girder at three levels as 5, 50, and 90 cm from the lower surface of the girder to measure the temperature gradient.

Fig.10 shows daily changes of vertical temperature distributions in the bridge from '94 September 2 22:00 as well as long-term one from '93 August 5 14:00 which gives the curvature of the bridge. Fig.11 indicates the change of deflection measured by the system compared with that obtained by the curvature. A positive value in the coordinate is warping and negative one is curling. Measured deflection shows rough agreement with calculated one up to September 3 14:00 and then these deflections show the difference. Although the temperature is measured only at a side surface of the girder and is not measured at upper portion as well as inner portion, the curvature of the bridge is considered to depend on the temperature distribution of whole cross section.

The change of deflection with time was also measured and that was compared with the result computed considering the effects of creep and drying shrinkage of concrete, as is indicated in Fig.12. Creep analysis was done based on the principle of superposition in which creep coefficient and drying shrinkage strain were determined according to CEB MODEL CODE 90. It is assumed that the girder was prestressed and loaded by dead weight at the age of 7 days, and then loaded by both deck pavement and handrail at 28 days. According to Fig.12, measured deflection agrees very well with calculated result, which means that the present system enables to measure long-term displacement with satisfactory accuracy. As is shown in Fig.12, the increase in deflection under sustained load is negligible and temperature change marked by black circles in Fig.10 influences strongly the change of deflection. The increase in creep and drying shrinkage during measurement for 4 months is very slight, because measurement was carried out at the age of nearly 2000 days after construction. To measure instantaneous deflection of the bridge, a transportation vehicle with full weight of 21.9 tonf was loaded on the span center in one lane of the bridge. Measured deflection was 2.2 mm and calculated one was 2.4 mm using the beam theory.

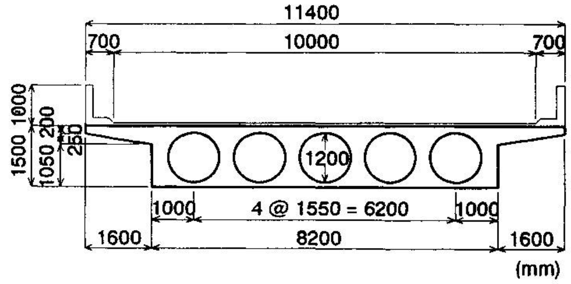


Fig.8 Cross section of the hollow girder

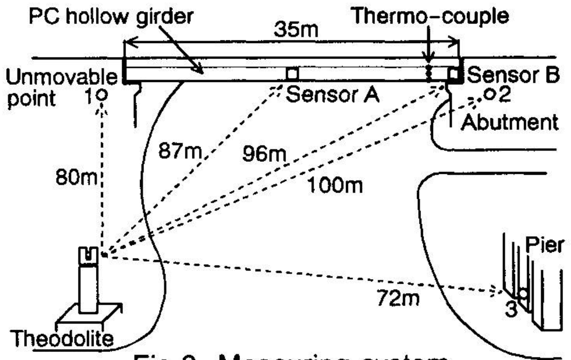


Fig.9 Measuring system

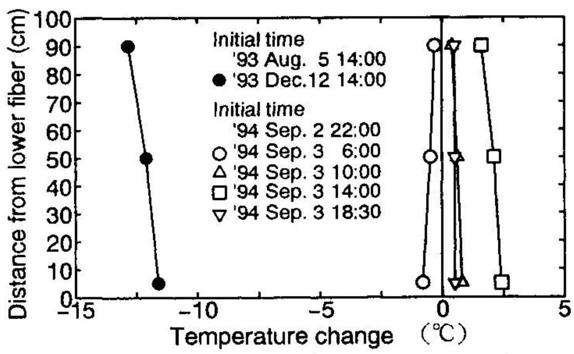


Fig.10 Distribution of temperature change

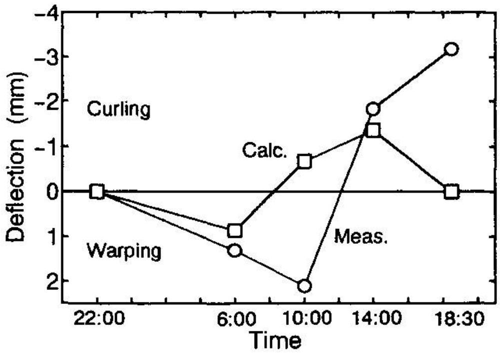


Fig.11 Daily change of deflection

4.3 Concrete Arch Dam

The 3-D displacements of concrete arch dam caused by water-level of the dam lake is measured by this system.

Two sets of theodolite with the launcher of laser beam are installed in the distance of around 150 m away from the dam and two sensors are attached on the dam. Using the output of a pair of sensors, the 3-D displacements of the structure can be calculated theoretically. The concrete arch dam to measure the displacement was built in 1994 which is 100 m high and has 300 m crest length. The measuring point is allocated on the downstream wall of the dam. The outline of measurement is shown in Fig.13.

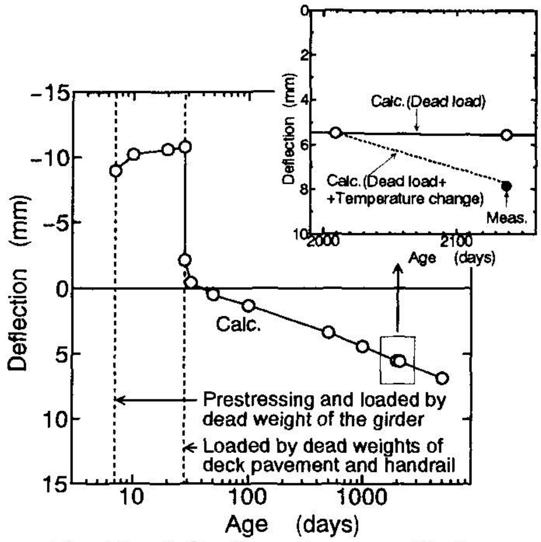


Fig.12 Deflection change with time

The measuring point is 20 m away from the center of the dam to the direction of the right river bank. The coordinate of 3-D displacements is also shown in Fig.13. The measurement was carried out in August and October 1994.

The displacement in the Z direction is shown in Fig.14. The displacement at the beginning of measurement at 9:00 A.M. in August 3 is assumed to be 0. The measured displacement in the Z direction at October 28 increased about 17 mm. This increase of the displacement in the Z direction is considered to depend on the water level of the dam lake, because the water level was around 90 m in August 3, and 75 m in October 28. According to another measuring system built-in the dam, 1 m change of the water level of the dam lake is corresponding to around 1 mm change in the Z displacement. The present measuring system can provide almost same value as the built-in measuring system. Using this system, the displacement of large size concrete structures like this arch dam can be measured accurately from the long distance. As for the measurement of long term behavior, the present system can be applied.

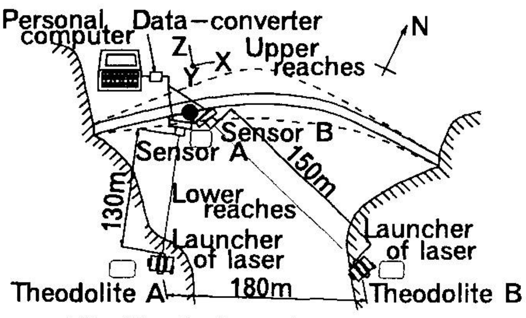


Fig.13 Outline of measurement

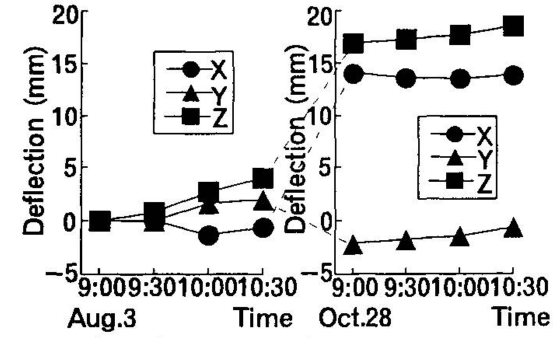


Fig.14 Results of measurement

## 5. CONCLUSIONS

The newly developed measuring system for long term displacement of large scale concrete structures is outlined. As presented in each application, the behavior of concrete structures can be explained by this system. Obtained information is especially useful for the maintenance of existing structures.

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