length and number of cracks. Small-scale cracking (i.e., few, short, narrow cracks) is expected to take place in all concrete; however wider, longer and/or more numerous cracks are not expected. It is possible to detect the formation of these cracks through acoustic emission sensors. It is also possible to monitor known cracks using strain gauges placed over the area of interest.

- **Location of rebar/delaminations** – The location of reinforcement in concrete can be determined using several non-destructive methods. These or similar techniques can be used to determine if the concrete above and below the reinforcement has begun to delaminate.
- Removal of soil can lead to instability of piers.

C. Concrete Metrics

- **Strain** – the relative elongation or shortening present in the concrete in specific locations of a bridge. In the service load range, the concrete behaves in a linear manner allowing the estimation of the stresses present at the particular location in the bridge.
- **Strength** – the strength of concrete is typically characterized from tests of cylinder or cubes that are cast at the same time and from the same mix as the bridge member or component. For determining the initial in-situ strength of the concrete, measurements of concrete temperature can be taken while the member or component is curing and compared to previously obtained temperature-strength correlations for the particular concrete mix. This can be useful for quality control of the concrete during construction.
- **Tension (in rebar/tendons)** – In post-tensioned systems, the tension in the cables is important to the overall strength of the concrete member. Also, if delamination occurs in reinforced concrete, the concrete cannot transfer forces to the rebar causing a reduction in stress. Thus, tension measurements can be used to assess the overall health of the structure.

D. Steel Metrics

- **Corrosion** – the chemical reaction whereby steel loses electrons to water and oxygen and other corrosive materials (e.g., road salts). Monitoring is useful in order to determine extent and rates of corrosion within the structure.
- **Crack Growth** – the elongation and/or widening of a known crack. Fatigue cracks may grow or remain static, with the former posing larger concerns than the latter regarding potential failure. Therefore, it is useful to a bridge owner to know if a fatigue crack is growing under the current loading conditions.
- **Cracking** – the number, width and length of cracks in a steel member or component at locations of stress concentrations or fatigue loading. Such information is useful for predicting the remaining life in a steel bridge or for averting a sudden failure. Quantification of cracking is important because extensive cracking at a critical location or member in a steel bridge can cause large changes in stresses at other bridge locations.
- **Strain** – the relative elongation or shortening present in the steel in specific locations of a bridge. In the service load range, the steel behaves in a linear manner allowing the estimation of the stresses present at the particular location in the bridge.
- **Tension (in cables) –** Cables in suspension bridges are designed to handle tensile forces. Monitoring the magnitude of these forces is of interest, especially in cases where bridge loads have increased beyond design levels, or if deterioration of the cables is suspected or known.

IV. Monitoring Systems Used In Bridges

The CSIR-CRRI has collected lot of data from instrumentation and monitoring of Highway and Railway bridges on National Highways and on the commercial routes of Indian Railways. These bridges offered a unique opportunity to design the instrumentation scheme matching with the needs of bridge management authorities and aiming at short and long term monitoring view. The data obtained from the field studies and their corroboration with the theoretical results yields a significant basis for strengthening of existing bridge information system (BMMS) for estimating lifetime characteristics of elements of bridges and predicting the future conditions of networks of bridges on Indian Highways and Rail network. The Information System for Bridge Networks Condition Monitoring under GIS Environment has been developed for Department of Science and Technology by CSIR-CRRI. The conceptual departure from the standard bridge management systems may be made using a novel stochastic process built out of the gamma process [5]. The statistical model can then be designed for the estimation of infrastructure lifetime, based on the analysis of more than 15 years of bridge inspection data already available and under study from these bridges.

With the help of a case study, pertaining to a national highway bridge on the river Ganges which incorporates the features of monitoring carried out (in different bridges) at various bridge components of the bridges, explains fallout of the measurement metrics. Instrumentation and monitoring of a twin cell prestressed box girder balanced cantilever" bridge was carried out in early 1990's right from the stage of its foundations [3]. A general arrangement of the bridge is as shown in Fig.2.

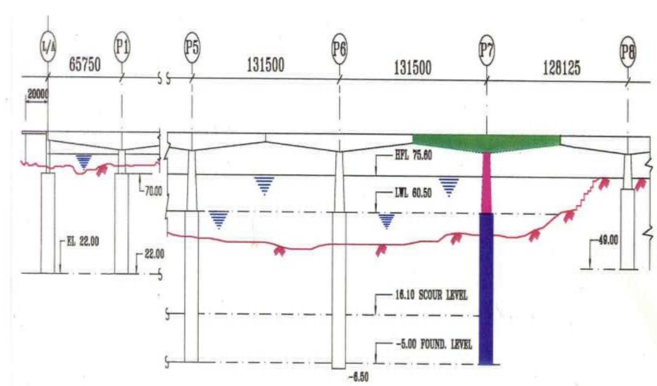

Fig. 2: General arrangement of the instrumented bridge by CSIR-CRRI.

The superstructure's arm P-7 of balanced cantilever bridge as shown in Fig. 2 was provided with "state of the art" instrumentation as considered appropriate at that point in time.

The features of the bridge and parameters monitored are described below:

- **The dimensions of the bridge:**

Well Foundation Depth = 65m

Diameter of well foundation = 13m

Height of Pier = 23m

Depth of box girder = 2.0m to 8.5m

Top width of box = 19.6m

Superstructure Segments= 2 to 4m, Max. Span= 135m

- **Parameters for monitoring:**

➢ **Well Foundation and Abutment** (Fig.3)
  - Lateral Soil Pressure
  - Hoop and longitudinal strain
  - Tilt/Inclination of well
  - Corrosion

➢ **Pier and Pier Head** (Fig. 4,5)
  - Tilt of Pier
  - Strains and Thermal Gradient

➢ **Superstructure** (Fig. 6,7,8)
  - Strains/stress
  - Accelerations
  - End Rotations/Tilt
  - Deflection
  - Temperature Gradient
  - Corrosion

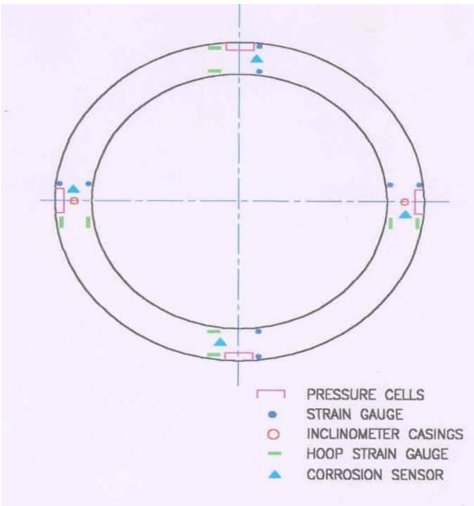

Fig. 3: Sensors for performance parameters in well foundation

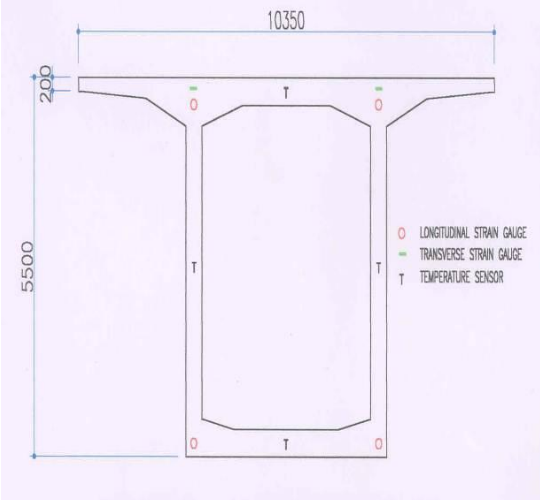

Fig. 4: Typical scheme for performance parameter in Pier head segment.

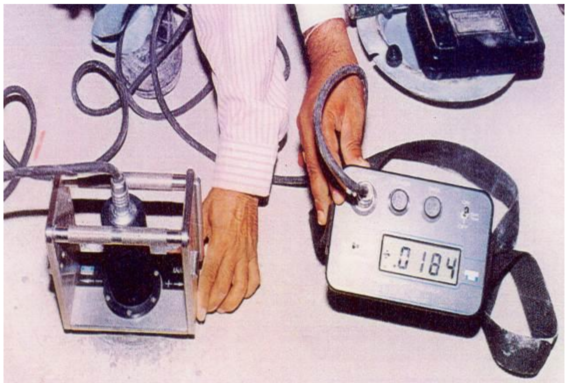

Fig. 5: Tilt/End rotation in Well/Pier/ Superstructure.

Fig. 6: Strain (Rosette) in pier/superstructure

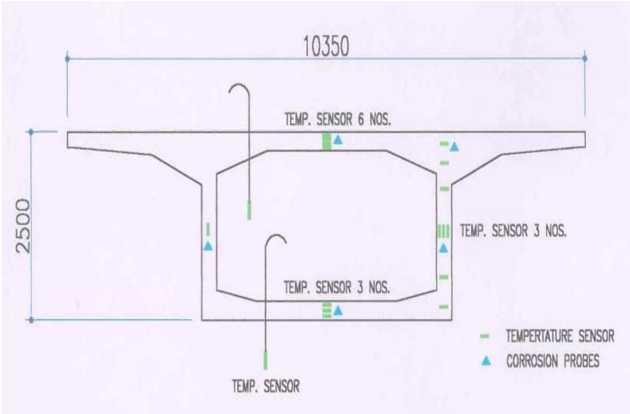

Fig.7: Location of Sensors at mid span section**.**

Fig.8: Corrosion sensors for monitoring of corrosion.

III. Monitoring Stages For Compilation Of Data In Bridge Management

In order to make use of scientific monitoring data into the bridge management system, a phased long term monitoring programme has been prepared and explained below:

Phase-1: **Installation of sensors and collection of data during construction and a set of base line data before opening the bridge to traffic comprises of following:**

- Detailed Planning of instrumentation scheme
- Preparation of Detailed specification for Procurement of various sensors and equipments
- Calibration/performance checking of sensors & equipments after procurement
- Installation of sensors as per construction schedule and the instrumentation scheme
- Preparation of test specimens for shrinkage/creep etc for laboratory study
- Collection of field data as per scheme i.e. during hardening of concrete, pre stressing, load test etc.
- Installation of data acquisition system for automatic collection of data
- Collection of base line data of all the installed sensors
- Structural integrity test for dynamic characteristics.

Phase-2: Long-term Performance monitoring of the bridge comprises of followings:

- **Monitoring during peak summer:** A set of measurements of all the installed sensors and diurnal (repetitive pattern) hourly variation of strain and temperature, deflection profile of bridge due to change in temperature.
- **Monitoring during peak winter:** A set of measurements of all the installed sensors and diurnal hourly variation of strain and temperature, deflection profile of bridge due to change in temperature.
- **Health status of structure through study of performance parameter:** Variation of all the performance parameters to be studied due to change in seasonal and diurnal temperature, losses of prestress and degradation material properties.
- **Development of degradation model:** On the basis of long-term data collected a degradation model has to be developed for prediction of remaining life of the bridge.

V. Conclusions

The paper describes only few features of bridge condition monitoring strategies implemented on a typical bridge by CSIR-CRRI. The result of continuous monitoring of performance parameters from the base-line data on long-term basis yields useful information to detect the early distresses in the structure. These results form the part of detailed inspection regime in the bridge management programme.

ACNOWLEDGEMENT

The above research programme was part of projects being sponsored by the Ministry of Road Transport and Highways and Department of Science and Technology, Government of India. Author acknowledges the help from Sponsors and Project teams associated from time to time by the CSIR-CRRI. The unstinted support and guidance from Directors of CRRI is gratefully acknowledged.

REFERENCES

[1] Donald Pearson-Kirk, Benefits of Bridge Condition Monitoring, Proceedings of the Institute of Civil Engineers, Bridge Engineering, 161, September 2008, issue, BE3. https://doi.org/10.1680/bren.2008.161.3.151
[2] Lakshmy P., Goel R., Goyal JK., Report on Infrastructure Information System for Bridges in GIS Environment, July 2011.
[3] Ghanekar VK, Tamahankar MG, Sahu GK, Goyal JK, Report on Long term Performance Monitoring of Balanced Cantilever Bridge on river Ganges, Varanasi, India- 1999.
[4] Premchand, Tamahankar MG, Sahu GK, Goyal JK, Report on Long term Performance Monitoring of Simply Supported Box PSC Girder Bridges on Thane Creek, Airoli, Navi Mumbai, July 2000.
[5] Khalid Abour and Bijan Samali, The Information System for Bridge Networks Condition Monitoring and Prediction, International Journal of Information Technologies and Systems Approach, 5(1), 1-18, January-June 2012 https://doi.org/10.4018/jitsa.2012010101

Mr. J. K. Goyal Born on 28.11.1966 did his B.Tech in Civil Engineering from MITS Gwalior and Post Graduation in Structural Engineering in 1990 from Birla Institute of Technology and Science, Pilani. He has more than 30 years of experience in R&D, project implementation and execution related to Highway and Bridge Engineering Projects involving multifarious tasks. He has carried out pioneering work in long term performance monitoring of the bridges and nuclear power structures. He has also accomplished instrumentation of many railway bridge projects for their capacity evaluation for Indian Railways. He has been the Chief General Manager and Project Director for implementation of National Highway Projects on various National Highways and Expressways of the Country. He has played a significant role in execution, planning monitoring and Policy framework for development of National Highways in India. He has published more than 20 R&D papers in National and International Conferences/Seminars/Journals and 50 national research reports.