Instrumentation and Monitoring Works – a Vital Part of Underground Construction

B. Suresh Kumar, Nishimatsu Construction Co., Ltd

ABSTRACT: In the development of underground infrastructure facilities, the instrumentation works are vital part of construction to monitor the work site and its vicinity to ensure overall safety. The significance of this work is emphasized highlighting the aspects such as the prevailing awareness in the industry, concept and objectives of instrumentation works, a rational approach in the design and implementation of instrumentation scheme, diligent interpretation of monitoring results, cost allocation and the need for an effective risk and hazard management system in underground construction.

1 INTRODUCTION

In recent years, the development of infrastructure facilities like underground transportation system is gaining momentum worldwide in metropolitan and cosmopolitan cities. Eventually, the construction often involves deep excavation and tunneling through developed area under challenging soil conditions. These underground structures are usually designed by engineers based on the set of codes derived from years of experience and empirical knowledge. The contemporary design of these structures uses advanced modeling and analytical tools with concept of factor of safety. However, the soil-structure interaction is still a highly complex engineering to predict the actual behavior of structures during construction. Thus the monitoring of the construction sites especially the deep excavations, the structures and utilities in the vicinity is of paramount important to ensure the overall safety of the construction staff and the public. In this context, quality instrumentation and monitoring scheme is a vital part of underground construction and essential for the successful construction and completion of underground structures.

2 MINDSET IN THE INDUSTRY

The instrumentation and monitoring works are no doubt an integral part of any construction project. However, in the past, the general mindset in the construction industry was this was viewed as a ‘specialist work’ rather than vital part of the project. Probably the two basic reasons could be, in terms of scale, it hardly takes around 1 to 2% of the total project cost and the lack of awareness in the industry on the importance of this tiny but vital activity. But in the recent past there are signs that the level of awareness has undoubtedly increased not only in the construction industry but among the building or land owners and the general public. The control of noise, vibration and ground movements caused by construction activities is a sensitive task for the builders to minimize nuisance to the adjacent properties and public. A recent instance stated in the news that the land owner has gone to the extent of installing his own noise meter to monitor the excessive noise from a nearby construction site, would substantiate this. It would not be a surprise in future, if the building owners would install their own instruments to monitor the ground movements around the buildings caused by the nearby construction works. This change in the trend is
probably a call for the construction industry to revisit the current work ethics, work culture, work attitude and the construction practices.

3 CONCEPT OF INSTRUMENTATION

The design of underground structures and deep excavations use the advanced analytical techniques like finite element model to predict the ground movements by simulating the various construction stages. Despite this, the prediction of failures or the warnings in advance may not always be possible in practice with out some sort of observation aids. This is due to the fact that the soil-structure interaction is highly complex and certain level of assumptions is made in the design. Besides these, the structures are inanimate and they have no life on their own to tell about the ‘pain’ they suffer due to excessive movements. The instrumentation and monitoring system as illustrated in the Figure 1 is similar to the nervous system in human body that sends symptoms of ‘pain’ or signs of sickness to the brain when the body gets sick. It is interesting to note that such integrated monitoring systems of a typical underground construction and its vicinity resemble human body as shown in Figure 1. It acts like an ‘intelligent system’ coupled to the structures that send warning signs and identify the hazards well in advance. The information from such intelligent system is also vital for the review of design optimization, construction control and for an effective risk and hazard management system.

![Figure 1. Concept of instrumentation](image)

4 OBJECTIVES OF INSTRUMENTATION AND MONITORING WORKS

The instrumentation and monitoring works have its role right from the feasibility study, through progressive construction and post construction stages of any major project. It is appropriate to disseminate the objectives of this significant work to all personnel involved in the construction. The key objectives shall be outlined as follows.

4.1 Pre-construction stage

At pre-construction stage of any major project, it would be a proactive approach and essential to establish the on going natural ground movements of the project site, the buildings and services in its vicinity with
instruments. This is in order to isolate the ground movements that would be caused by construction activities from the prevailing natural movements. The instruments are also essential to establish the actual ground water table level and to identify critical areas that exhibits sensitive soil conditions to be considered in the design and construction techniques.

4.1 Design

At preliminary design stages, the instruments are essential to establish the design parameters through pilot or trial tests for the periodical design review during construction to verify the basic principles, concepts, assumptions and parameters for optimization of design.

4.2 Construction

The prime objective of monitoring works during the construction is to monitor the overall stability of work site to ensure safety of all personnel involved in the construction especially in deep excavations and tunnels. Secondly to monitor the overall stability of buildings, structures and the network of utilities in the vicinity those do not exceed the tolerable movement and suffer any damage due to construction to ensure public safety. Thirdly the ‘observational method’ of construction to ensure proper construction control to decide on the changes in the construction sequence and methodology by verifying whether the structures behave as designed. Finally to monitor and ensure the movements of completed structure and the vicinity at post-construction stages for proper hand over of reinstated site.

4.3 Risk management

An effective risk management in any project greatly relies on the diligent monitoring and reporting system to indicate advance warning on the risks and hazards during the construction. This is a proactive approach to gain ample time to decide on the preventive and contingency measures in case of established alert levels are breached. Moreover to establish a system to integrate the design, consultants, monitoring, construction and safety personnel to identify risks and hazards well in advance during construction and respond during crisis.

4.5 Insurance

Last but not the least, to provide substantial information for technical assessment and causation reports meant for insurance claims and legal disputes by adjacent land owners in case of unforeseen incidents.

5 DESIGN AND IMPLEMENTATION OF INSTRUMENTATION SCHEME

5.1 Rational Design Approach

The success of an instrumentation and monitoring scheme largely relies on a rational and robust approach in the design to install the right instruments at strategic locations and depths along the deep excavation or tunneling site. The preliminary design of instrumentation scheme involves proposing series of instrument arrays at specified interval around and along the excavation areas and tunnels. This is probably good enough to quantify the instruments for budgeting and procurement purposes. However, in order to make the overall scheme as functionally optimized and cost effective, the preliminary design need to be fine tuned through an overall reorganization of the instrument arrays by taking in to consideration the factors highlighted in Figure 2.

The typical section of an instrumentation scheme for an open cut deep excavation is shown in Figure 3. This illustrates the strategic locations of various instruments to monitor vertical movements of ground, building and utilities with settlement markers (L), sub-surface vertical movements at different depths by magnetic extensometer (MX), lateral ground movements with inclinometer (I), base heave inside the open
cut excavations with heave stake (HM), ground water drawdown and seepage by piezometers (P), loads in the strutting system with strain gauges and load cells (SG/LC), tilt of buildings with electro level beam (EL) besides vibration and noise monitoring of buildings in the vicinity.

Figure 2. Factors to be considered in the design of an instrumentation scheme

Figure 3. Typical instrumentation scheme for a deep open cut excavation section
5.2 Establishment of influence zone of construction

Based on the type of underground structures, construction methodology and predicted ground movement contours due to construction, the estimated zone of influence shall be established prior to start of construction. As illustrated in Figure 4, the primary influence zone depends on the type, width and depths of the underground structures. The secondary influence zone is literally difficult to predict and site specific. It may extend into few hundred meters and depends largely on the prevailing geology and soil stratifications of the site. It is essential to accomplish the pre-condition survey and damage assessment for all the structures and services in the influence zone and especially for those identified as sensitive prior to the start of construction. The review levels are normally established based on such damage assessments.

Figure 4. Influence zone of an underground construction

5.3 Phased implementation

The next crucial step that follows the rational design is the implementation of the instrumentation scheme at right location and time at site. In the underground construction, the construction activities are vast, scattered and often involves movement of heavy machinery in limited space. In order to minimize the damage of instruments and make it functionally effective, it is wise to implement the scheme in a phased manner in accordance with the master construction program. The installation of instruments in one stretch is otherwise susceptible to damages despite adequate protection. The site constraints such as the machinery movement areas, diversion corridors of roads and services and their time frame, visibility, accessibility for monitoring and protection of instruments against vandalism especially those proposed to be installed outside construction premises are key factors to be considered during the installation of instruments at designated locations. In general, the suggested phases for the implementation of the instrumentation scheme for an infrastructure tunnel project are as follows.
5.3.1 Phase 1
The instruments to monitor the general ground water level with tidal fluctuations and ongoing natural ground settlement in the vicinity at preconstruction stages including instruments meant to establish the preliminary design parameters.

5.3.2 Phase 2
The instruments to monitor the sensitive buildings, structures and utilities (especially joints of high voltage power cables, gas, water and sewer mains) in the influence zone of the construction.

5.3.3 Phase 3
The instruments outside the open cut excavation zones meant to monitor vertical, lateral ground movements and to assess the trench stability in the vicinity of retaining system construction.

5.3.4 Phase 4
The instruments to monitor the trial and pilot test zones and at green field sites above bored tunnel with more instruments at the initial drive zone to establish the design and tunneling parameters respectively.

5.3.5 Phase 5
The proposed instruments inside the open cut excavation zones with adequate protection meant to monitor the basal heave and seepage potential zones prior to commencement of excavation.

5.3.6 Phase 6
The instruments meant for the monitoring of strutting system for the open cut excavation and for the convergence measurement inside the constructed bored tunnel rings that are installed as the construction progresses.

6 INTERPRETATION OF MONITORING RESULTS
Subsequent to the implementation of the rationally designed instrumentation scheme in a phased manner, the key phase is the diligent interpretation of monitoring results is to identify the potential risks and hazards well in advance during the construction. The question of interpretation of monitoring results is very subjective. It is not just limited to comparison of monitoring results with established review levels but rather an analysis of the results on a broader perspective in conjunction with design, construction and safety aspects. The engineer who interprets the monitoring results shall have comprehensive information about the basic principles and concepts of design, construction methodology and sequence, geology of site, thorough knowledge about various instruments and their manufacturer’s recommendations, interactive behavior of soil, structure and instrumentation and the tell tale signs observed at site. Most importantly it is the integration and correlation of all these information to identify risks and hazards with good engineering judgments.

A simple and informative reporting format of monitoring results of various instruments is essential to facilitate a full pledged interpretation. One such typical presentation format for a deep excavation is illustrated in Figure 5. The changes in the trend of ground, structural movements, base heave, the piezometric level and ground water draw down with respect to construction sequence and time, are the key observations to be made while interpreting the results to identify the hazards and risks on a global perspective.
7 RISK AND HAZARD MANAGEMENT

In an underground infrastructure projects, a systematic risk and hazard management is of paramount importance in order to ensure the overall safety of the site and its surroundings. In the instrumentation and monitoring perspective, the management of identified risks and hazards in any project is a sheer team work with close coordination and sharing of information among the construction personnel. In this context, as illustrated in Figure 6, a ‘risk management committee’ shall be formed to integrate designers, consultants, academicians, and construction, geotechnical, instrumentation and safety personnel. They represent clients, builder and specialist sub-contractors to assess and implement the contingency plans through close coordination in case of emergencies. It would be a proactive approach to establish the contingency plans in advance for each potential risk and hazard identified so as to implement on time when the situation warrants.

8 COST ASPECTS OF INTRUMENTATION SCHEME

In terms of cost, the instrumentation and monitoring works take around 1 to 2% of the total project cost depending upon the location of site, sensitivity of adjacent properties and prevailing challenging soil conditions. The latest innovations in information technology make it possible a centralized automated
monitoring of the whole construction site and its vicinity on real time basis. Perhaps the initial establishment cost of the automatic monitoring seems to be expensive, but it is cost effective and reliable over the long span of construction period. It is wise to make use of the soil investigation boreholes or install the instruments close to the existing boreholes, incorporate existing instruments if any at the project site, rational design and phased implementation to minimize damages in order to make the scheme cost effective. Despite protection of instruments, the damages of instruments are inevitable as the construction activities are vast and often involve heavy machinery. So it is prudent to consider 10% of the total quantity of instruments as a buffer in the design of instrumentation scheme to cater to the replacement of damaged instruments. A provisional sum of maximum of 2% of the total project cost shall be allocated for the instrumentation and monitoring scheme of any underground construction and is currently in practice in the industry.

Figure 6. An integrated risk management system

9 CONCLUSIONS

The instrumentation and monitoring works are integral and vital part of an underground infrastructure development. The intended purpose of this work is not limited to design optimization and construction control but to ensure the safety and stability of the work site and its surroundings with advance warnings and alerts. It may not be an exaggeration to state that ‘like safety, instrumentation and monitoring is the responsibility of every personnel involved in the construction’. It is essential that every personnel involved in the construction to have the basic knowledge and orientation about the instrumentation and its significance on the overall safety of the work site. In the development of underground infrastructure facilities in confined metropolitan areas, the roles and responsibilities towards the instrumentation and monitoring works are not only limited to construction staff but extends beyond the construction premises. The regulatory authorities, statutory boards, utility agencies, professional engineers, consultants, builder, sub-contractors, land and building owners adjacent to construction sites have their respective roles and responsibilities towards this tiny but vital work. An integrated risk and hazard management system shall be established to effectively manage the underground construction projects.