INSTRUMENTATION IN TUNNELS

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STATE OF THE ART

Instrumentation in tunnels is significantly related to design and construction problems. An instrumentation program is most valuable for monitoring the project, designing future tunnels, and advancing the state of the art. Instrumentation should be considered a tool for extending the capabilities of the observer. In some cases, instrumentation may consist only of simple settlement surveys and other information normally available on the project. In other cases, specialized instruments may be required to obtain useful results. The following are areas of concern in instrumenting a tunnel; they are similar to those for designing and constructing a tunnel.

1. It must be possible to advance the tunnel safely and to maintain the integrity of the opening. Displacement measurements, using borehole extensometers, are the most useful methods for monitoring the stability of an opening. Such instrumentation is particularly applicable for large underground openings, where it is possible (a) to monitor the effects of the various excavation sequences in time to permit adjustments in the excavation and support of the later sequences or (b) to modify the support in the portions of the opening already excavated. An engineer or shift foreman, even though capable of visually evaluating the support requirements in a single heading, is not able to assess the overall stability of a complex system of multiple openings. Instrumentation integrated into the design and construction process can provide the needed information.

2. Construction of the tunnel must not excessively damage adjacent or overlying buildings, streets, or utilities. This requirement is of primary concern for tunnels in soil. In a rock tunnel, stability of the opening is usually most critical: If the stability can be maintained, then the rock displacement will not be great enough to damage adjacent or overlying structures. However, in a soil tunnel soil displacements can result in damage to nearby structures even though the stability of the tunnel is maintained. Instrumentation to monitor soil displacements is used to assist the designers in evaluating the need for underpinning and in helping the contractor determine which construction procedure is causing ground to be lost.

There are two major aspects in the measurements of soil displacements: The first is to evaluate the movements immediately adjacent to the tunnel so that they can be correlated with construction procedures and so that the source of the lost ground can be determined. If the cause of the ground movements is known, corrections to the tunnel procedure can often be made to minimize lost ground. The second is to determine the distribution and magnitude of lateral and vertical displacement away from the tunnel that could damage structures. Once this distribution is known, the extent of underpinning required or the damage limits can be evaluated for various amounts of ground lost into the tunnel. Displacement measurements for evaluating damage to adjacent structures consist primarily of settlement surveys at the ground surface near the tunnel. The settlement surveys involve deep settlement points to determine lateral displacements both at the surface and at depth.

3. The tunnel should be capable of withstanding all the influences to which it may be subjected during its lifetime. Initially, the lining must be able to support the tunnel as it is excavated. Instrumentation can be used to measure the loads and distortions imposed on the initial lining as it is erected and as the heading advances away from that portion of the tunnel. Such instrumentation is often difficult to install and protect in the congested heading. The instruments must often be installed and read in a short period of time as the heading advances away from the instrumented section. Instruments that can be installed prior to construction or that require a minimum amount of assembly in the tunnel are to be preferred.

Instruments on steel ribs may consist of strain gauges to evaluate thrust and moment. Thrust can also be measured by placing load cells beneath steel ribs. Distortion measurements can be made by using tape extensometers and tunnel surveys. Strain gauges embedded in shotcrete can be used to correlate strains with cracking of the shotcrete.

The observations described above do not provide much information on the adequacy of the permanent lining for the life of the tunnel. In many tunnels a permanent lining is installed after the initial lining has stabilized the tunnel. Initially, stresses and strains developed in the permanent lining are related primarily to shrinkage and temperature effects during curing of the concrete and are secondarily related to soil or rock loads. If the soil or rock is creeping and distortion of the initial lining is still taking place as the final lining is installed, soil or rock loads will develop with time on the permanent support. Such loads can be measured, if the instrumentation has long-term stability.

Described below are some of the measurement systems that can be used in tunnel instrumentation.

1. Borehole extensometers and settlement probes are installed in boreholes and measure displacements parallel to the borehole. An extensometer may consist of nothing more than an anchor in a borehole and a rod extending from the anchor to the collar of the hole. The position of the rod with respect to a reference surface anchored at the collar can be measured manually by using a depth micrometer or dial gauge. Extensometers may be installed in boreholes from within the tunnel. The reference surface is at the collar of the hole in the tunnel, and anchors are located at various distances from the collar of the hole. So that a complete history of displacements can be obtained, extensometers can be installed in advance of excavation from a nearby excavation or from the ground surface.

Because the extensometer measures a relative reading from the collar of the hole to the anchor, it is desirable to install one of the anchors for the reference surface at a point that is outside the zone of expected significant movement around the tunnel. If all anchors and reference surfaces are located within the zone of movements, then a survey point should be tied into the top of the extensometer. Extensometers can be read to 25.4 μm (0.0001 in) by using a depth micrometer or dial gauge; thus, the instrument is sensitive for use in rock tunnels, where displacements as small as 2.54 mm (0.01 in) may indicate potentially unstable conditions.

Around soil tunnels, settlement probes rather than extensometers are usually adequate. The settlement probe consists of a rod anchored at the bottom of a borehole. The movement of the anchor is measured by surveying the top of the rod. The settlement probe thus has the accuracy of a normal settlement survey.

2. Over soft-ground tunnels, a survey of the settlement profile at the ground surface can be combined with the survey of settlement probes anchored immediately above the tunnel. In this way both the source of the lost ground and the distribution of settlement can be evaluated. It is particularly important to tie the settlement survey to a stable bench where regional settlements occur in compressible soils because of groundwater lowering. Such settlements extend many diameters away from the tunnel.

3. The inclinometer measures displacements perpendicular to the axis of a borehole. The inclinometer, in combination with settlement points and extensometers, can be used to obtain the three-dimensional pattern of movement about a tunnel. The inclinometer consists of a slope-measuring torpedo that rides in a grooved casing. The inclinometer torpedo measures the inclination at specific intervals in the casing. These inclinations are summed to determine the lateral displacement of the casing with respect to some fixed reference point in the casing. Inclinometer torpedoes available in the last 5 years have improved accuracy and repeatability over units previously available. A servo-accelerometer type of torpedo unit has repeatability of approximately 2.54 mm (0.01 in) over 3 m (10 ft) of casing length.

4. Strain gauges can be installed in or on the support to estimate thrust and movement in the section. Strain gauges can be either mechanical gauges (such as the Whittemore gauge), vibrating wire gauges, or electrical resistance gauges.

5. Distortions of the tunnel lining can be measured by using portable tape extensometers attached to hooks on the lining. Displacements can be measured by using tensioned tape extensometers to a precision of approximately 2.54 mm (0.01 in). Settlement surveys can also be used in the tunnel to evaluate settlement and vertical distortion of the lining crown and invert that is greater than 2.54 mm (0.01 in).

FUTURE RESEARCH

Interpretation of Displacements Around Soft-Ground or Mixed-Face Tunnels

One of the primary concerns in soft-ground and mixed-face tunneling is limiting displacements that can damage nearby structures. Data are needed to correlate sources of lost ground with ground movements that can affect nearby structures. Accurate records of construction conditions should be correlated with measured ground movements. Surface surveys should be supplemented by deep settlement points, and readings should be made with time as the tunnel is advanced by the measurement cross section.

Instrumentation for Large, Shallow Openings in Rock, Soil, and Mixed-Face Conditions

Multiple drift techniques, ground stabilization, and presupport techniques will be required in large, shallow openings such as those constructed for highways or subway stations in urban areas. In such projects, instrumentation can evaluate these techniques and provide information on stability, the ground displacements affecting nearby structures, and the conservatism in initial and permanent support capacity.

Improvements in Instrument Reliability, Ease of Installation, and Ability to Read Instruments

Instruments providing the needed accuracy for measurement are available. There is a need for improving their reliability and developing a system of rugged instrumentation that can be used by field crews to provide a comprehensive picture of tunnel performance.

Integration of Measurement Program With Field Observations and Construction and Design Requirements

The most valuable information and greatest benefits will result from instrument programs closely related to design and construction objectives. Programs have failed in the past because this coordination did not exist.

Manual of Instrumentation for Underground Construction

Instrumentation of underground construction is a comparatively new technique. There is need for more literature on the subject for guidance of design engineers, geologists, and contractors. A manual or handbook on tunnel instrumentation, compiled by a knowledgeable individual or agency, should prove useful.