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Engineering Geology in Conservation of Heritage Monuments and Sites

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Unique and priceless remains of our cultural heritage are endangered all over the world. These cannot survive long without good care. Their large number, variety and value make their conservation a huge and complex task. Interest in conservation of rapidly decaying monuments especially in urban areas has increases appreciably in last 4-5 decades. Many of the masterpieces have been declared 'World Heritage' by the UNESCO. Considering the vital role of engineering geology in this conservation, the International Association of Engineering Geology devoted its 18th international symposium (1988, Athens) to 'The Engineering Geology of Ancient Works, Monuments and Historical Sites'.

Archaeological monuments are damaged by the environmental effects over time as well as by human actions. The natural damage suffered depends on the structure, its age, composition of its materials, its geological setup, and the severity of injurious atmospheric agents. Increased urbanization and pollution seem to have accelerated the process.

Variety of construction among monuments is obviously as wide as the range of human activity over time (spanning from dwellings, buildings for various uses, water supply and disposal structures, communication structures, etc., to tombs). Starting from a simple natural cave with crude paintings to a complex and sophisticated construction with elaborate ornamentation, everything is found. Similar is the range of building materials and technology used in these monuments.

Conservation principle demands that any permanent intervention must ensure the preservation of current appearance of the monument and its close surroundings. Also the materials used for this must perform well in long term and the treatments should be reversible. The preservation of archaeological ambience is, therefore, a complex issue in practice. Agreement lacks among archaeologists on the nature and extent of acceptable change due to the conservation works. Opinions vary from puritan, disallowing any human interference on the ground of maintaining originality, to permitting even reconstruction to any necessary extent in order to maintain the monument for posterity. Even burial has been suggested for preservation in some cases. Clarity on this point is essential in the conservation project concerned, for planning geotechnical investigation and for appropriate choice of the treatment methods and materials.

Since materials and processes of the geoenvironment constitute, support and/or damage the monuments, geological study is basic and vital for their long-term conservation. In response to this need a new specialized field of engineering geology, termed 'restoration geology' by Prof. R.Di Stefano, President, ICOMOS (International Council on Monuments and Sites) is taking shape.

Difference from normal engineering geological practice

The engineering geological aspect of monument conservation work is no different from that of construction or mining activity, in principle. The methods and techniques of study and ground improvement/protection are broadly the same. However, there are

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differences mainly on the following counts, which make the conservation more complex and challenging.

1. Invaluable and irreclaimable nature of monuments
2. Age and fragility of monuments / antiques
3. Archaeological constraints in application of technology
4. Technological constraints of knowledge for the sensitive work
5. Supposedly everlasting monuments
6. Fixed locations

The techniques have to be applied in such a way that there is no chance of damage to the structures to be protected. There is almost no tolerance for failure which may jeopardize the irreplaceable and often fragile heritage. This requires extremely careful, expert handling, since, the structure may be very old and already weakened or damaged by ground movements, weathering, etc. The preservation and protection works undertaken must continue to perform their function throughout the extended lifetime of the structure and safely be replaced after that since the heritage is supposed to last for ever. The works often attract intense public interest and must meet the demands of archaeologists & architects who require the works to perform well without causing any change in the appearance or architectural value of the structures being protected. There is not enough scientific/technical knowledge on several aspects to ensure long lasting or even safe treatments. For such needs the technology is being tried and tested by careful laboratory and field research to meet the stringent demands of the already fragile antiques. Geotechnically unsuitable locations of numerous monuments, selected for the contemporary preferences, pose a problem that can not be tackled as conveniently as in the normal engineering geological practice of changing site or reorienting a new construction. Since heritage is invaluable, cost is not such a controlling consideration as in most other works.

Since, state of the art technological and scientific inputs are often needed to solve many issues, multidisciplinary specialized services / advices are important in conservation work. It demands a high degree of expertise from the engineering geologist as well as high quality inputs from other collaborating professionals (notably geophysicist, geotechnical / structural engineer, various laboratory and field testing / instrumentation specialists). Besides the state of the art technology and research, close coordination among the concerned experts is often essential to assure impeccable quality. It is an important task to identify and manage the monument specific multidisciplinary needs of conservation, and responsibilities and interaction of various scientific & technical personal, in the picture.

Variety of geotechnical problems

Most problems threatening monument safety are broadly similar to those affecting other constructions. However, the above mentioned factors especially the time element and stringent restrictions and expectations, make some additions.

Foundations

Though the reasons for foundation problems in monuments are similar as in other civil structures, some aspects related to their antiquity are, however, peculiar to them. The poor understanding, in older times, of the foundation materials, their behavior under loads, and of structural methods of construction to suit them, have in many cases been responsible for damage. Foundation overloading by repeated building heightening and differential movement between adjacent buildings are examples. Historical changes in ground water and sea levels and slow neotectonic processes have also affected the foundations at places. Decay of elements like foundation mortar, wooden piles, etc. has reduced support. The common geotechnical measures of foundation consolidation, support, drainage, etc. have been adopted to save the structures since historical periods and hence with varying efficacy.

Slope instability

Slopes above, around or below the monuments are mostly natural and therefore often highly affected by prolonged progressive distressing and weathering. Often the sites chosen for defensive, religious and other such reasons are too close to cliffs for safety, and threatened or damaged by frequent rock falls/ slides. Technique of computer simulation and physical tests are used to examine the paths of rock falls to establish the best locations for defensive works below a rock face. The tests determine through the morphology of the rock slopes, how a falling rock would splinter on impact and the paths that rock blocks would follow. Inaccessibility poses an important problem in study and exploration of the scarps and execution of treatment on them. Adequately safe arrangements are required to take man and material to difficult locations. Slope cutting it generally infeasible at archaeological sites since it may drastically change ambience. Elaborate temporary measures (nets, housers, rock fences, impact walls, etc.) may therefore be needed before work. Drilling is done from scaffold mounted drills with the whole system anchored to rock for necessary propulsion. Specially designed machines to drill on high, very steep slopes, without scaffolding are also used. Photogrammetric and laser scanning techniques are used for geotechnical studies without access.

Archaeological excavation

Besides their own stability, the stability of adjoining existing structures becomes an important consideration especially when archaeological excavations are deep or close to buildings and other constructions. Drainage, dynamic pore pressure increase and viscoplastic flow in soils and highly weathered materials need assessment and control. Since, desirable level of prediction is difficult even with the state of art, monitoring is also important, especially with usually unknown construction history of the site and surroundings.

Underground works

The underground ancient works and monuments suffer from the fundamental problems of material decay due to weathering or creep. Weathering, as a result of water seepage, changes in temperature, etc. modifies both material and discontinuity properties and thus give rise to all sorts of problems ranging from damage to sculptures and wall decorations by block falls, to roof collapse and day-lighted openings. Creep, the time dependant loss of strength, affects the stability of entire opening and would not directly affect architectural or artistic features contained within it. Many well known methods of repair and stabilization are applied. But it does not seem possible to recover the ravages of weathering and creep.

The concept of stand-up time of a new underground opening based on the premise of stability assessment nearly at the time of excavation, dose not provide for the variety of progressive deterioration by different processes over such time span. In the context of ancient openings it perhaps needs redefinition to consider progressive loss of rock mass quality. The drastic fall in supporting capacity of the thinner structural members like pillars, walls, arches, etc., over long period is a particularly important aspect to be taken into account.

Walls

Critically unstable structures pose the question of optimal way of restoration, the choice between strengthening verses dismantling and rebuilding. Conservation of unstable dry stone walls is complex, since, introduction of mortar can change its structural behavior and future weathering pattern drastically, while dismantling and rebuilding generally dose not improve stability of such walls. Placing high strength & resistant (stainless steel or fiber) wires and meshes inside wall, spot glued to blocks, is suggested. In retaining walls, special anchoring devices have to be designed to use resistant points in the weak wall and ground.

Building & replacement materials

Repair needs may vary from replacing a highly decayed small part of a statue to mending an entire weathered masonry wall. Detailed study of the composition and behavior of the materials used in a monument is essential for its proper preservation. It is considered best to use the same stone as the original, in the repair and restoration works of the ancient buildings and other monuments. However, microcracks due to wrong quarrying (uncontrolled blasting, etc) can significantly increase porosity and hence weathering susceptibility of the repairs. Suitable substitutes, based on matching appearance and geotechnical properties are used if the original is not available. Natural rock or composite (with controlled properties) substitutes are used. When source of original stone is doubtful, provenance is determined to locate it by its detailed study. In adding new, better quality replacement materials the bonding and differential behavior of old and new material may be problematic. Material compatibility is especially important with the more sensitive soil structures.

Sources of ancient materials

Determination of true sources of stones used in monuments is an important archaeological problem. Knowledge of provenance of the stones is required for archaeologically proper reconstruction of broken monuments, statuary and inscriptions, etc. This knowledge is also helpful for the authentication of artifacts of doubtful nature. Ancient rock sculptures can be copied but not their weathering patina. Various petrographic and geochemical analyses / studies are needed to precisely match the source. Some classical quarries have been identified from significant statistical differences in trace elements. Database on sources is needed to use these techniques.

Pore water damage

Porosity controls moisture & salt content, distribution, circulation, and their contact area with minerals, and hence influences strength and weathering of stone. The pore moisture participates in more actions on stone than any other agent. It hydrates, hydrolyzes and dissolves the minerals, and transports chemical reagents and bacteria. Mainly the acidified or alkalized waters cause solution and attack minerals until saturation. Rock moisture is derived mainly from atmosphere and ground, by gravity, osmotic, and capillary action. Because the common rocks are hydrophilic, water can penetrate extremely small openings.

Water inhibiting minerals may swell and thereby facilitate disintegration. Interlayer hydration of some iron hydroxides and anhydrite, or intake of the water of crystallization also causes swelling. Crystallization of dissolved salts on water evaporation exerts pressures and causes spalling from rock surface. Resistance to crystallization damage decreases as the proportion of fine pores increases. Crystallization pressures in small pores are appreciable (gypsum exerts pressure up to 100 MN/m^2; anhydrite 120 MN/m^2; and halite, 200 MN/m^2) which are sufficient to cause mechanical disruption.

Stone can be damaged by the repeated wetting and drying. Thermal expansive force of pore water can particularly damage stones of low tensile strength by gross fracture. On temperature rise from 0°C to 60°C it expands about 1.5 % and can exert a pressure up to 52 MN/m^2 within the pores. Diurnal variation of 40°C can develop pressure around 26 MN/m^2. On freezing water expands by some 9 % and can act like a wedge at the apices of pores. Pressures of up to 210 MN/m^2 could be developed at -22°C. Pore structure governs the degree of saturation and the magnitude of freezing stress. The risk of frost damage increases as the saturation coefficient approached the critical water content (the lowest amount of moisture which causes expansion of the stone on freezing; 75 to 96 % of total pore volume). The rapidity with which a stone attains its critical water content is governed by its initial state of saturation and its ability to absorb further water.

Artificial vibrations

Several human activities cause ground vibrations with damage potential. Frequency range of 10 to 50 Hz is the main susceptible area. Limiting peak particle velocities of 2 to 8 mm/s have been proposed for different types of vibrations to prevent damage to ancient structures. Transient or continuous nature of vibration and type and condition of structure under consideration, are important in assessment of susceptibility. Velocity transducers with recording unit are normally used to record particle velocities in three orthogonal directions. Multi-channel digital data recording simplifies data processing for vector resolution of the three components, and frequency analysis, etc. While road traffic vibrations are considered too mild to cause damage to ancient structures, those from heavy freight trains may be potentially risky, and pile driving may generate high-risk vibrations.

Seismic hazard

Seismic study of ancient monuments serves the duel purpose of extending the seismological record to past and protecting the monument against this hazard. The monument is examined for all signs of damage/collapse which are measured, critically evaluated with respect to structural peculiarities of monument, for seismic origin, and dated by suitable methods. A more realistic recurrence interval for the assessed magnitude is found. Similar orientation of tilt / damage / collapse all over the monument, deformation of and closer to floor, cracking of most vulnerable parts, reconstructions / reinforcements / repairs with earthquake-resistant design, along with absence of evidence for other causes of damage, indicate seismic damage.

Occurrence of earthquake in future, the seismic hazard, implies uncertainties. Therefore, probabilistic forecasting and decision making are inevitable in hazard analysis. For reasonable safety over a certain time interval, the maximum seismic load tolerable by monument (design load) should not be exceeded within it. Probability of this safety condition may be found from extreme value distributions statistics of earthquake magnitudes.

Earthquakes pose a major risk for many monuments, since seismic loads may be critical for the ancient rigid structures. Estimates of maximum expected earthquake magnitude and resulting peak ground motion parameters (acceleration, velocity, displacement) at the monument site are needed to find the maximum dynamic load a monument may suffer in a defined period, for designing its protection measures. These estimates are made from (known or modeled) seismic source distribution and geometry (point, line or area) in the region, maximum earthquake generating potential of each source, and attenuated seismic load contributed by each source to the site, through intervening medium. All contributions are convolved to give the net probabilistic loading at site.

Seismic risk evaluation for restoration / reinforcement of monuments requires survey of vulnerability of the monuments besides the seismological record, geological-geomorphological-geotechnical characterization of the area, and survey of weak zones in foundation materials. Analysis of this information leads to identification of (i)critical areas, (ii)zones with different seismic behavior(microzonation), and (iii)most vulnerable constructions. For more realistic risk analysis, response of a microzone to earthquake is further classified by a 'soil index' based on relative ratings of various geotechnical parameters of the individual building sites. Vulnerability classes are based on ratings of type, design, structural parameters and maintenance condition of monuments.

Restoration of historic cities

Conservation and restoration of historic towns has to be integrated with their development and adaptation to modern life. This needs town planning for subsurface transfer / creation of several facilities, which need not necessarily be on ground, in order to preserve the historic ambience while increasing their functionality in present context. Engineering geological contribution is fundamental to underground development work on such scale.

Relocation

Archaeological remains discovered at new construction sites, are required to be relocated to safer places. These are often soil or stone structures weakened over time and difficult to handle. Work involves elaborate reinforcing, repair, grouting or packing of joints, packing the chambers with insitu fills (e.g. foamed polyurethane) for support while moving, separation of structure by close spaced boring, hoisting, moving and setting. Relocation is also required to save the monuments from impending hazard like predicted volcanic damage, submergence by new pondage, etc. Complete dismantling and rebuilding of masonry structures has been done.

Aesthetics

There is archaeological need to make the stabilization works as inconspicuous as possible, but there is little literature on the means of doing this. Sometimes the preservation work appears more impressive then the monument. In the case of cable anchorages, which must be accessible in order to allow checks on cable tensions, this may be excusable, but other works may be disguised. Bolt face plates can be hidden if recessed. Besides using suitable dye in concrete to match the rock color, the local rock may be used as aggregate wherever suitable and the visible surfaces of concrete may be molded to resemble the natural rock. Concrete covers to protect completely weathered surfaces, have been cast insitu behind shuttering of fabric reinforced epoxy panels, pre-molded on rock face, in order to give natural appearance of outcrop to the concrete surface. Grout seepages may be coated with dye to blend with the color of the rock face, Greater aesthetic disturbance results from the tonal contrast after cleaning of vegetation, though minor revegetation can soon reduce the disturbance.

Vegetal damage

Damage due to vegetation is common and sometime serious problem of monument sites, yet it appears a less studied area particularly with regards to rock which is more prone to vegetal damage. Root penetration significantly damages buildings, foundations, slopes, etc. Rock slopes are more vulnerable to such damage where tree roots mechanically open the joints and facilitate entry of water for its various damaging actions. Even after tree removal, decay of the roots left in rock discontinuities will be a source of organic acids as also is the surficial vegetal debris. Transmission and effect of forces of severe wind to fragile slope through trees seems an almost untouched area.

Prediction of future changes

Complexity of the subject of monument preservation and protection is multiplied by the changing environmental parameters and their effect on the monuments over their indefinably long life span. Speed of change apparently accelerated by human contribution to pollution is itself uncertain. Detail and long-term studies of the critical processes and parameters affecting the various materials, structures, etc. are needed to assess future changes in the monument/ site for remedial decisions. Minor movement along a crack or seepage water quality at the site may, for example, change to unsafe levels during the long life of a rock-cut monument.

Special study needs and methods

Besides the normal engineering geological and geotechnical investigations for site characterization, some more studies, specific to nature and needs of archeological conservation are required. Following are the geotechnical methods and practices commonly used in the studies for conservation.

Prioritisation

Larger monuments often suffer from a variety of problems. The extent and complexity of problems may be too large to be handled simultaneously, with due care, within available human and material resources. Locations and work components are therefore prioritized from a preliminary study done for their identification and grading. Priority is dictated by concerns of safety and archaeological value of monument. Interlinked issues may complicate the procedure.

Monitoring

Some currently active changes need careful and often long term systematic observation for understanding and quantified analysis of the problem to predict its damage potential. At monuments of high tourist interest it is important for human safety also, and in critical cases should be coupled with warning system. Progressive deformations are measured / monitored by precision surveys, tell tales, strain & stress measuring instrumentation, acoustic measurements, etc. Recognition of hazardous structural elements and safety thresholds, and keeping watch for violation of threshold over time due to natural changes or artificial actions, are attempted. At places rapid coastal, alluvial or wind erosion deserves close observation. Rainfall (site specific) and seepage need elaborate monitoring. Continuous rainfall record is more useful than the daily figures. Need for critical microclimatic data varies with climatic regions and pollution levels.

Petrography

Detailed petrographic study of the stones is basic to monument preservation. Its main objectives are rock and mineral identification, macroscopic description of deterioration for classification, microscopic study of weathering damage, pore space characterization, detailing of deleterious components (clay minerals, soluble salts, microcracks, etc.), correlation of composition and texture with mechanical / hydraulic test results, source determination, understanding decay mechanisms, identifying gaps and outlining alternative/advanced studies, and resolving sampling problem for various tests. Microstructure analysis is especially important for rating the stone behavior. Advanced methods of mineral physics and chemical detection are commonly used for specific problems. In view of vital and wide role of petrography, 'Group Petrography' was created in 1977 by ICOMOS (International Council on Monuments and Sites) as a forum for promoting petrographic solution in conservation of stone monuments.

Porosity & water migration

Generally low porosity stones are more durable than high porosity stones. Detailed characterization of pore space where physico-chemical and biological processes occur, is important for weathering study. Though pore size determines the movement of moisture within a stone, it alone is no guide to durability without the data on distribution of pores.

It is extremely difficult to measure the real pore space due to its chaotic nature, but it can be described by statistical parameters. These data can be obtained by direct measurements of optical and electron microscopy coupled with image analysis system. Suction plate method and the mercury porosimeter are most commonly used to indirectly measure porosity and investigate the distribution of pore sizes accessible to the measuring medium within a stone. Total porosity and pore radius distribution are determined. Reliable characterization of pore space can be done by combination of optical microscopy and mercury porosimetry. These laboratory tests are an important part of damage investigation and essential for preservation and conservation measures. Modification of pore structure by stone preservative is studied to know the distribution of preservative in the pore space.

Saturation moisture content and rate of water absorption are rough measures of pore size distribution. The saturation coefficient (volume of voids that are accessible to water) is the ratio of effective porosity to total porosity. High value of saturation coefficient (0.95) indicates a stone of rather low durability, whereas one with a value of 0.4 should be highly durable. The natural absorption capacity of a stone is the quantity of water which can be absorbed readily while the total absorption capacity is the amount absorbed after a prolonged period of soaking, say a year or more. The coefficient of capillarity measures the rate at which a stone soak up water. It has been related to frost resistance. Moisture tends to move towards the narrowing end of a capillary and if there is a difference in temperature across a stone, moisture migrates towards the colder side.

Weathering classification

The conventional engineering geological classifications of weathering grade are too broad for archaeological work, where small changes in material are significant for damaging the appearance or integrity of an object. Local concentrations of run-off guided by façade geometry cause differential weathering and marking patterns on carved surfaces. To manage decay, elaborate classification of weathering damage based on numerous weathering forms (discoloration, salt and biogenic deposits, relief, crusts, disintegration, detachment, etc) and their subdivisions is designed. Quantitative petrographic and chemical analyses are needed for quantifying the decay.

Weathering on building walls and rock-cut faces, as also on natural outcrops, shows different patterns in different parts of the same rock due to differences in exposure and microclimatic conditions in different parts of the structured or curved surface, sculpture, etc. Very large scale maps showing areal distribution of rock types and their decay are prepared. Petrographic and chemical measurements are needed for quantifying the decay.

Weathering rates

Weathering potential of the material-environment system is evaluated by accelerated weathering tests in laboratory and long term measurements on sample surfaces exposed to actual environment. Fresh, weathered and treated rocks are subjected to accelerated weathering in laboratory for simulation of weathering. Besides standardized tests like acid immersion, sulphate crystallization, and freeze-thaw tests, etc. the influence of single weathering factor or combination of site specific natural factors are checked. The material changes are evaluated in fine details by various analytical and measuring techniques. Results of the simulation tests allow a prognosis of the weathering behavior of stones in the monument and its improvement by chemical treatment. However, the laboratory weathering tests still have many limitations in simulating nature and need improvement based on deeper understanding of the natural phenomenon being copied.

Long-term insitu weathering rates have been measured on tombstones using thickness difference between top and bottom, micro relief of resistant inclusions, etc. Tombstones provide large number of identical specimen with dates for statistical treatment and thus have potential for predicting stone decay for conservation as well as for construction in their environment. Long term, orientated field exposure of test samples to real environment, against better-studied standards, has also been tried for weathering evaluation.

Chemical preservation against decay

Weathering decay of rock monuments necessitates their protection from atmospheric agents. Stone preservatives are materials used to prolong the life of stone by either restoring its physical integrity or by retarding its decay. The preservatives must not change the appearance or architectural value of the stone. Ideally a preservative should perform as intended for a desirable length of time, which is yet among the most difficult questions. Use of chemicals is preferred on areas difficult to access for repeated maintenance. Vacuum impregnation, brushing, spray and injections are used to deliver the chemicals. For consolidation or preventing migration of soluble salts, the chemical should not choke the pores of stone and restrict movement of vapors in stone. It should line the grains without filling the pores and pore connections.

Chemicals have been used as surficial water repellents, impregnations, consolidants, and sealants for cracks etc. Water repellents have been applied to the stone surface to provide a protective coating (2-3mm thickness) and to bind friable material together. Surface treatments do not create a totally impermeable skin, and have been mostly unsuccessful and even harmful (e.g. surficial repellents, notably silicones and siliconates; and consolidants like siliconester). Many chemicals are therefore developed for deeper impregnation (25 - >50mm), which prevents contact between the soluble salts (concentrated near surface in the decayed zone) and water besides making the treated layer resistant to crystallization damage. Sealant is meant to penetrate the surficial network of fractures to seal the migration / exchange of fluids across the exposed rock surface. However, they present the possibility of extension of microfracture network due to the modified thermal gradient on the new surface.

Performance data of preservatives especially for long time is not available. Most of the common epoxy resins are too viscous to impregnate the pores of stone. Monomers show good penetration into porous structure as compared to analogous polymers. Some of these with many qualities of a good preservative have performed better than many chemicals. More promising monomers are methacrylic, acrylic and alkoxy-silanes. The former show better improvement in physical parameters, especially compressive strength and ultrasonic velocity of rock samples.

Monument mapping

It is very detailed mapping of individual archeological object, statue, cut or made face, etc. needed for delineating type, defects, extent and distribution of the stones used and precisely documenting their damages. Investigation method has been developed to record in detail the weathering damages according to objective and reproducible criteria. Decay is mapped visually and samples are taken for laboratory analysis to characterize and classify different kind and degree of decay. These maps on scales like 1:50 or even larger, are the basis for evaluation of the damage situation. Damage type and intensity distribution with respect to the orientation, construction form, and detailed geometry of mapped surface, is fundamental for damage analysis. By repeated mappings the state of monument can be monitored for long term. Mapping results can be quantitatively evaluated by measuring procedures. Quantification may require calibration with carefully taken thin, shallow, cores. Near surface damage quantification in detail allows precise planning of treatment at micro level. Sonic, resistivity, and GPR techniques are helpful in extrapolating the units and features mapped, into the depth zone of interest.

Photogrammetry and laser scanning

State of the art practices are needed for characterization of inaccessible areas. Digital photogrammetry and laser scanning with suitable data processing software, are used to create measurable virtual rock outcrops and models of buildings that may be visualized and analyzed in 3D from any viewpoint. Monuments are commonly found on, in or below rocky scarps, steep slopes. Terrestrial photogrammetry with phototheodolite enables, besides 3D viewing, structural mapping of such slopes and petrographic mapping of weathering walls of high buildings, without direct access. It is suitable in limited distance range and fairly accurate to track long-term changes / deformations also. Photographs are processed by a stereocomparator to obtain point coordinates for contouring, geological mapping, analyzing structures, and drawing building elevations. Software enables rapid acquisition of measurements in 3D. Tall building faces have been mapped for lithology and weathering with average accuracy less than a centimeter, by stereophotography with a terrestrial metric camera mounted on a lifting platform.

Laser scanning can cover longer distance range and generates 3D point cloud models of objects without scale. It is accurate, fast and economical for creating high quality DTM. If big surface is modeled from small patches, fitting errors arise which have to be edited by the user. Combined use of laser scan and photogrammetry can fully capture the geometry of any object. By fusion of images taken by the two methods models of architectural objects with surface textural information can be generated.

Geophysical exploration

Since, disturbance at the ancient monument sites should be kept at a minimum, the non-invasive methods of geophysics have great valuable in deciphering the geotechnical parameters. Besides investigation of covered areas they are needed to provide sufficiently detailed characterization of the near surface weaker / loose mass in 3-dimentional including its subdivision into geotechnical units of uniform engineering response. Considering the importance and sensitivity of monument sites it is prudent to use geophysics applicable to site, liberally and for crosschecking the results by different techniques. Specialized equipment are developed and designed for gaining high accuracy and resolution over small areas. The less expensive geophysical work can ensure safe and economic data acquisition by minimizing the invasive exploration, which could be difficult, and very costly at such sites, due to stringent quality and monitoring demands, and sometimes even unsafe. Developments in GPR, crosshole seismics, and tomography (seismic, electrical, and GPR), are very promising, though the later two usually need drilling.

Isotope & trace element study

Isotope studies have been used to solve the critical archaeological problems of determination of provenance of the stone used for monuments and artifacts, association and reconstruction of broken statuary and inscriptions, and their authentication. Ancient rock sculptures can be copied but not their weathering patina. There is significant isotope fractionation according to origin and weathering. In weathering, original oxygen isotopes of rock exchange with meteoric oxygen. In case of Greek and Roman marbles stable isotope ratios $^{18}O/^{16}O$ and $^{13}C/^{12}C$ have provided distinctive values for many quarries and the marbles used in artifacts. $^{87}Sr/^{86}Sr$, dependent mainly on the isotopic composition of original seawater, was also found useful as geochemical signature of sources. Some classical quarries showed significant differences in trace element patterns by computer-based pattern-recognition. Besides statistical handling to overcome the inherent variability of rock material, trace element studies may require many samples. Database on sources is prerequisite to use these techniques.

Research

Sufficient site-specific applied research involving detailed laboratory and field investigations, is often required on various materials, procedures, and other aspects before designing remedies for monuments. Some of the important areas are vibration tolerance of monument to the various sources of disturbance, including the exploratory and execution works, choice of rock bolting / anchoring systems, and selection of chemicals for consolidation, impregnation, coating, and grouting applications.

Documentation

Conservation works like all engineering works, require maintenance and this can only be done if adequate records of the works done are retrievably saved for future reference. Preparation of a detailed record of the works done should be a precondition of complete work. Detailed photodocumentation before and after treatment is valuable. Documentation is especially important due to the long life and sensitivity of monuments.

Contribution of archaeology to engineering geology

The interactive archaeological and geological studies have enhanced engineering geological understanding in the following areas, by extending the observable evidence of geoenvironmental response to human activity into the deep past.

Neotectonism

Buried, submerged or elevated historical remains indicate relative subsidence or uplift of their sites. Examples are particularly common in costal areas where water level is a general reference surface for such change. Molluscan borings present on pillars well above present water level, buried civilization along Indus Valley, deep erosion in canal beds below original level, are some cases indicating neotectonism. Where original form of the old structures is known, deformation of ruins indicates occurrence as well as geometry of movement. The Great Wall of China built 400 years ago is dislocated by a fault for which right lateral land vertical slips have been calculated from the shift in wall.

Dating

Archaeological remains especially artifacts, are often used to date geological features for gaining authoritative limiting dates. This dating can be applied to a wide range of environment, especially when combined with historical information. It sometimes has much greater resolving power than other dating methods, e.g. a well-controlled local pottery sequence may make dating within a few decades possible. The resolution increases as we approach present since the duration of stratigraphic divisions based on technology decreases. At the other extreme, however, the best archaeology can do is to separate material of human manufacture (anywhere in last 3 million years in age) from older material.

Seismicity

Seismic study of ancient monuments enables valuable extension of the seismological record into past, for which there are few means available. If the monument damage found to be of seismic origin, could be dated by suitable archaeological or other methods, a more realistic recurrence interval for the assessed magnitude is found.

Geotechnique

History and gradual progress of civil and geotechnical engineering is revealed critically by the geotechnical studies of monuments. Long term performance record of a large variety of constructions, building materials, and construction and treatment methods in equally wide range of geological and climatic conditions, exists in the form of the numerous archaeological monuments all over the globe.

Monument conservation studies in India

Monument conservation in India is being done since historic times, yet engineering geological - geotechnical studies for conservation on a rather systematic though insufficient basis seem to have begun with the multidisciplinary study of Ajanta and Ellora world heritage monuments in Aurangabad, Maharashtra, by the Geological Survey of India in 1998. The project was sponsored by the Archaeological Survey of India. Pitalkhora caves (Aurangabad), Gwalior fort monuments (Gwalior), Gairaspur temple (Vidisha), Bhim Bethika world heritage monuments (Raisen) and Aurangabad caves (Aurangabad), are some other monuments studied since then in central India.

Geotechnical aspect of the work done so far is mostly rather preliminary. Geophysical and microseismic investigations were also done in a few cases. The studies generated information useful for planning detailed geotechnical investigations which, however, demand specific and intensive resources. Detailed geotechnical studies of Ajanta and Ellora monuments were taken up with the available resources. Initial remedial suggestions have been made on issues that do not demand further geological detailing or where temporary intervention considered urgent for safety could be worked out. Environmental studies, usually an important component of the work done, have contributed significantly to the upgradation of environment around some of these sites, particularly Ajanta and Ellora.

The more challenging structural conservation of rock-cut monuments on adequate geological-geotechnical basis, seems a little touched field in India. Given the wealth of our heritage monuments and the lack of geotechnical resources (at any one point) needed to guide their scientific structural conservation, the relevant indigenous expertise and resources need to be inventoried, pooled, enhanced, and channelised on national level, to meet the challenge of conserving this wealth for posterity.

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