
International Conference on Case Histories in Geotechnical Engineering (1984) - First International Conference on Case Histories in Geotechnical Engineering

07 May 1984, 11:30 am - 6:00 pm

Foundation Performance of Very Old Structures

S. C. Handa

University of Roorkee, Roorkee, India

Follow this and additional works at: <https://scholarsmine.mst.edu/icchge>



Part of the [Geotechnical Engineering Commons](#)

Recommended Citation

Handa, S. C., "Foundation Performance of Very Old Structures" (1984). *International Conference on Case Histories in Geotechnical Engineering*. 23.

<https://scholarsmine.mst.edu/icchge/1icchge/1icchge-theme1/23>

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in International Conference on Case Histories in Geotechnical Engineering by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact scholarsmine@mst.edu.

Foundation Performance of Very Old Structures

S. C. Handa

Professor & Coordinator, Q.I.P. Centre, University of Roorkee, Roorkee, U.P., India

SYNOPSIS: Withstanding the agents of destruction for several centuries, some of the structures in this world, exist as a testimony to the sound and perfected techniques of construction used in years that belong to the bygone past. Among the most famous are Taj Mahal and Qutb Minar, still standing in a magnificent and sound condition. One of the wonders of the world, Taj Mahal though built in seventeenth century still looks so fresh that the super-structure performance also speaks of the adequate and perfect foundation that must have been built for it. This paper deals with subsoil conditions at site, the type of foundation, its construction technique and its performance for a very long period for both Taj Mahal and Qutb Minar.

TAJ MAHAL

INTRODUCTION

A very few sights are better than the rumour of their beauty and Taj Mahal is one of them. Near the battlefield of Burhanpur, on 17th June 1630, exceedingly beautiful queen Mumtaz Mahal died while giving birth to her fourteenth child. But before she died, Mumtaz Mahal made king Shah Jahan promise that he would build a tomb that would remind the world of their great love. It took him twenty two years with twenty thousand men to create this jewelled mausoleum upon which people from the world over have gazed in wonder for its beauty, elegance, grace, charm and radiance for more than three centuries. The construction started in 1631 and was completed in 1653. In the city of Agra in India- there it stands - one of the most beautiful and most magnificent monuments ever built by human hands, (figure 1).



Fig 1: Locations of Cities and Monuments

The imposing main entrance gate leads one to the lovely garden, symbolizing Paradise, having a marble tank in the centre and a water channel with a row of fountains in front of the Taj. The Taj itself is located by the side of river Yamuna on a square marble terrace. On the four corners stand four tapering minarets. In mausoleum, the central upper hall has a latticed screen of carved marble containing cenotaphs of Mumtaz Mahal and Shah Jahan. The real graves of the queen and the king are at a lower level. Shah Jahan is also buried in the Taj Mahal though he never intended it so. Several architects and builders from India and abroad helped Shah Jahan to achieve his dream of constructing a tomb with no parallel anywhere else. All the world salutes them today for having built a monument - so magnificent, so sublime, so exquisite and so strong both below and above the ground level. The main tomb is built in white marble and is studded with precious and semi-precious stones, (figure 2).

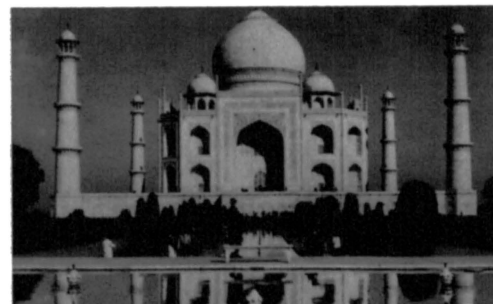


Fig.2: Taj Mahal at Agra

SUB SOIL PROFILE

There are no historical records available for sub soil profile at the site. Nor there had been an attempt on the part of the Government to ever make a borehole at site to know the details of the subsoil and the foundation to quickly analyse and face any threat, if it ever arises. However, a few years ago, to run the fountains and to maintain the water supply for the nursery and the garden, a tubewell was installed in the nursery area of the Taj complex. The strata chart obtained in the tubewell boring throws light on subsoil details giving a chance to make some geotechnical evaluation, (figure 3).

G.L.	Depth below G.L. (feet)	Thickness in feet	Strata details
	9.8	9.8	Clay
	34.5	34.5	Clay with kankar
	44.3	8.2	Kankar
	52.5	2.6	Fine sandy clay with kankar
	55.1	7.2	Kankar
	62.3	7.2	Kankar
	85.3	23.0	Sand stone with fine sand
	114.8	29.5	Clay with stone
	155.8	41.0	Sand with kankar and sand stone
	218.2	62.4	Clay with kankar with sandwiched layer of sand and stone
	229.7	10.5	Sand stone with sand
	292.0	62.3	Clay with kankar
	339.6	47.6	Clay
	388.1	48.5	Clay with kankar and sand stone
	393.6	5.5	Fine sand
	433.1	39.5	Clay with kankar and sand stone
	441.0	7.9	Clay

Note:- (Not to scale)

Fig.3:Sub strata details obtained through a tubewell boring at Taj nursery

The boring upto 441 feet below ground level indicates absence of rock upto this large depth. The site is in area having deep alluvial deposits where the depth of rock sometimes can be very large. Below ground level there is a layer of 9.8 feet of clay followed by clay with kankar upto 44.3 feet depth. This is underlain by 8.2 feet deep kankar layer, followed by 2.6 feet deep fine sandy clay, 7.2 feet of kankar and 23 feet deep deposit of sandstone with fine sand. Then there exists 29.5 feet deep clay with stone and 41 feet deep sand with kankar and sandstone upto a depth of 155.8 feet below ground surface. This is followed mostly by deposits of clay with impregnations of kankar and sand at times and with sandwiched layers of sandstone and sand at some depths as shown in

figure 3.

The science of soil mechanics was hardly known to the constructors in India in the seventeenth century, but they did had a very rich experience of heavy foundation construction based on post performance experience of early foundations. This experience had been accumulated and was carried over from generation to generation. If this experience of several centuries was a guide, then they must have thought of constructing a deep and solid foundation to carry rather heavy loads of the superstructure. And for that reason they could have thought of placing the bottom of foundations on the layer of sandstone with fine sand starting at 62.3 feet depth and having a thickness of 23 feet

FOUNDATION AND OTHER DETAILS

The main tomb is constructed on a white marble square platform having a side dimension of 3 feet and having a minaret at each of its corners with heights of 132 feet. The tomb containing graves is on a square of 187 feet with cut out edges to give it a depth effect. The total height of the monument above the garden level is 244 feet. It is a very heavy massive structure and the dome alone at its springing weighs about 12,000 tons and the walls of the cenotaph hall carry and transfer a pressure intensity of 8 t/sq.ft. Massive piers and vaults were constructed to support such heavy pressures before transferring them to well foundations underground. To cope up with the bursting effect of heavy stresses, an efficient system of headers and stretchers reinforced with iron clamps was adopted.

The drawings of the foundations must have been prepared with utmost care to carry heavy loads of the superstructure, but unfortunately they are no longer available. However, some of the details of the foundations are recorded in "Badshahnama", a contemporary text. Because of river Yamuna touching the monument on the North side and the ground being a slope of its bank and thus the deposit being of flood origin the entire structure was made to stand on a compact and solid bed of masonry. At lower level stone-in-lime masonry was used and in the upper region brick-in-lime masonry was used when possible. At the base of the foundation system a series of deep wells are provided. Their depth is not mentioned in the records but on the basis of borelog given earlier, it can fairly be guessed that they must have been taken down to rest on the layer of sandstone with fine sand starting at 62.3 feet below ground surface. The well steining consisted of stone in lime mortar while the inside of the well was filled with rubble-in-lime. A suitable number of wells were capped together to raise piers which were joined with vaults above. The masonry bed was supported above this and the arches were also included inbetween. The foundations were planned in accordance with the details of the superstructure so that massive piers and walls could rest on a suitable series of wells. Thus an effort was made to provide a platform consisting of a firm and compact base which was 43 feet above river level originally. Though the piers and walls of the superstructure rested directly on a series of capped wells, yet the whole

foundation system was so bonded together that it acted as a single compact body thereby minimizing the danger of differential settlements and hence cracking in the superstructure. An imaginative drawing of the foundation system based on the available description is shown in figure 4.

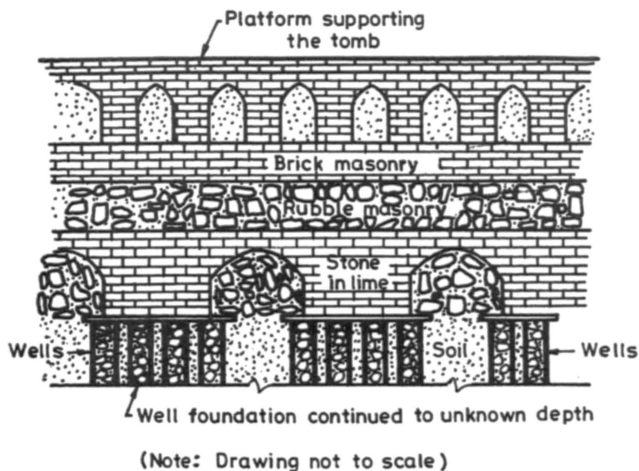


Fig.4: Imaginative view of foundations based upon available description

The danger from the thrust of the waters of meandering river Yamuna were well realized by the constructors. Wells were also installed along the foundation on the river front. In addition wooden boxes filled with rubble have been located which serve as shock absorbers to avoid transmission of water shocks to the main structure, (figure 5). Series of wells away from the platform wall were also installed in the river bed to lessen and absorb the fury of river water and avoid any danger to Taj Mahal. These wells had been filled with sand and mud and were provided with wooden axles and spokes inside. These wells were constructed with bricks in lime mortar.

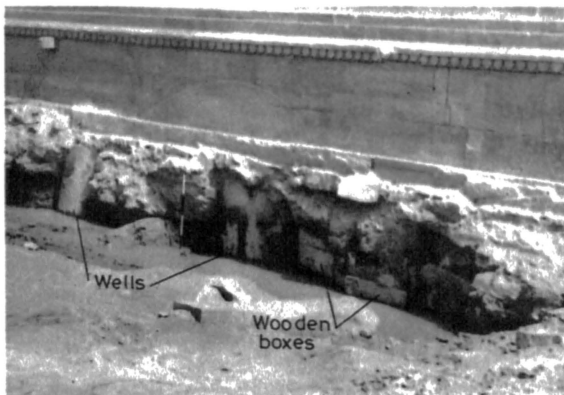


Fig.5: Exposed well foundations and wooden boxes under North wall.

DAMAGE AND REPAIRS

In spite of the best possible construction undertaken, there had been some problems with Taj Mahal from time to time. After four years of its completion, Aurangzeb (Shah Jahan's son) first noticed the cracks in the seven underground chambers after unprecedented floods that occurred in the river Yamuna and reported the same by writing a letter to Shah Jahan. To prevent this from happening again, two precautionary measures were undertaken. Firstly, a groin wall was built in the position of maximum scour. Secondly rubble pitching was done at the base of the wall adjoining the river in the form of rubble masonry in wooden crates. The intermediate spaces between the wooden crates was filled by rubble masonry in lime mortar. The dome of the holy tomb also leaked in two places and some galleries and arches in the second storey and four smaller domes had developed some cracks and were repaired. The repairs were also conducted between 1810 to 1814 by Captain Taylor. The restoration work was undertaken in 1874 by Alexander. A national committee was set up in 1937 to conduct an exhaustive survey with regard to the damage to this monument. It was found that the plinth of the mausoleum on the north (riverside) is lower by 1.44 inches compared to its level on south side. No cracks in exterior wall were noticed, but they were found on the second storey vaults and more intensely on the underground vaults on the north side. The four minarets at the corners were also found to be out of plumb by the following amounts:

S-E Minaret	-	4.5 inches
N-E Minaret	-	1.9 inches
N-W Minaret	-	1.4 inches
S-W Minaret	-	8.5 inches

The above tilts obviously for a height of 132 feet is not dangerous. In 1947, a total of 104 benchmarks were fixed on the different parts of the foundation and plinth and their levels recorded and also the verticality of the minarets was monitored. Subsequent checking of these in 1953 and 1958 did not show any difference, thus proving the inertness and the soundness of the monument. However, with the growth of civilization along the river banks in the modern times, the river changed its course and its point of maximum scour also shifted. Two spurs have been constructed recently to train the river suitably so as to avoid any danger to the structure. Though the above details do suggest some alarm at times, yet the pattern of cracks, appearance of leakage and tilting of minarets do not indicate any major foundation problem and the superstructure appearance after over three centuries does prove that the foundations have behaved in a superb and adequate manner.

QUTB MINAR

INTRODUCTION

In the middle of a monotonous plain, stretching out beside the river Yamuna, lies Delhi - the capital of India, a modern city studded here and there with ruins and monuments of the past several centuries. Among them stands its landmark called "Qutb Minar" on the outskirts

of this city, (figure 6).

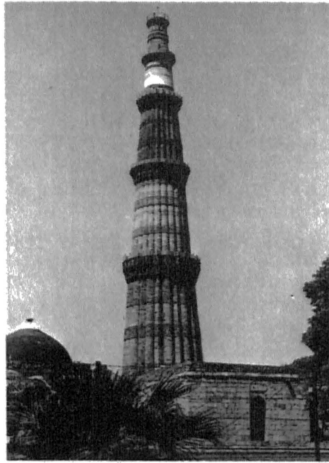


Fig.6: Qutb Minar, Delhi

The construction of this Victory Tower was started in 1199 by Qutb-ad-Din Aibak, who could raise it only upto the first storey consisting of a height of about 95 feet. His successor Iltutmish finished the minar by adding three additional storeys on the top. In 1368, lightning damaged the minar seriously and the then ruler Firoz Shah Tughlak got it repaired exhaustively, replacing the damaged top with two short heightened storeys. Originally, the minar had only 4 storeys faced with red and buff sandstones but presently the minar consists of five storeys as a result of this reconstruction having extensive use of white marble in the top two storeys. The present total height of the minar is 238 feet 1 inch which is divided into five storeys with the help of balconies. The original 3 storeys are each laid on a different plan, the bottom storey having alternate semi-circular and angular flutings; the second having semi-circular and the third having angular flutings only. The fourth and fifth storeys are plain. The base diameter of the minar is 47 feet and the uppermost diameter is 9 feet. The plinth of the pillar is 2 feet in height. The heights of various storeys alongwith corresponding sectional plans are shown in figure 7. The minar consists of an inner solid shaft and an outer shell having an opening in between which carries the stairs from bottom to the top. An ascent of 379 steps to the top of the minar discloses a great panorama.

DAMAGE AND REPAIRS

After its completion, the first damage was done to the minar in 1368 when it was severely struck by lightning. Firoz Shah Tughlak repaired the minar and rebuilt the present top two storeys. Lightning again struck and damaged the minar during the reign of Sikandar Lodi who restored it in 1503. Later, it does not seem to have received any worthwhile attention till early nineteenth century when it was

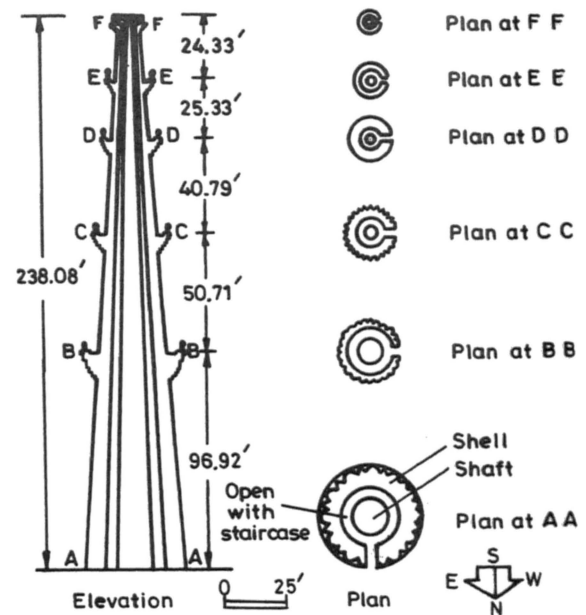


Fig.7:Sectional elevation and plans of Qutb Minar

standing in a terribly damaged condition because of weathering agents acting over a period of centuries and also as a result of severe earthquakes of 1782 and 1803. On the first of August 1803, the old cupola of the Qutb Minar fell down and the whole minar was seriously injured by this earthquake. Later, the exhaustive repair work was entrusted to Major Robert Smith who spent over two years to get the repairs completed in 1828 at a cost of Rupees 17,000 (about 1700 dollars). The repair work proved extremely beneficial as the minar thereafter successfully withstood the earthquakes of 1829 and 1905. Some repairs were carried out in 1920. Also, in early forties, it was noted that the veneer and particularly inscriptional bands had bulged out at places and a few buldges and twists had also appeared on the shaft. Major structural repairs were executed during 1944 to 1949.

In 1964 the officer-in-charge of the monument expressed concern over the development of cracks in the stones of the minar and requested for a thorough examination of the monument. A Qutb-Minar Committee was then set up by the Government to look into the various aspects of this monument, which during its investigations found that Qutb Minar not only had cracks in its super structure but was also leaning towards South-West direction by 2 feet 1 inch at the top. The foundation investigations were carried out and the foundation was strengthened by cement grouting in 1972. The superstructure repairs were also carried out in the first storey and are planned to be done throughout the height of the minar.

FOUNDATION DETAILS AND SUB-STRATA

A trench was excavated around the minar from east to west direction in 1965 which revealed that Qutb Minar rests on an open jointed ashlar mason pedestal 54 feet square and 5 feet 6 inches high

This is underlain by a platform 4 feet high and 61 feet square built in rubble masonry in lime. The trench indicates that on the eastern side, this platform lies on lime concrete but on western side it is supported on thick rubble packing in mud mortar, there also being a thin intervening soft layer of 4 inches thickness. On the west side the trench was sunk to a depth of 27 feet, but the natural soil or the bottom of the foundation was not reached. There was also a loose rubble packing against the vertical face of the foundation on the eastern side. The masonry immediately below the minar was found to have sunk thereby producing an inward slope of 1:4 in the south-western direction and 1:8 in the eastern direction.

For the heavy loads and tall height of the minar, it had been believed for a long time that the minar would be resting on rock underground. The geophysical investigations were undertaken and resistivity measurements suggested that bedrock is located somewhere between 150 to 200 feet depth. This estimate would look uncertain for the fact that quartzite bedrock is exposed at the ground surface in nearby area to the minar. However, a study of the geology of Delhi and the subsoil profiles do confirm that the rock in Delhi sometimes have very sharp dips and the depth to the bedrock below ground level may vary rather too quickly over small horizontal distances. But one would wonder as to why the minar was not constructed on bedrock on a nearby location. The reason could only be its relative location to the mosque which was built by destroying and altering the existing temples. In order to have better idea about subsoil conditions, two boreholes were drilled in 1970. Borehole 1 was located in south-west direction and was inclined at 45 degrees and goes beyond the centre of the minar upto a depth of 35 feet. The second borehole was located in north-east direction and was inclined at only 10 degrees and was bored upto a depth of 33.6 feet. From the subsoil data, it can be seen that the strata is rather heterogeneous and consist mainly of quartzite stone with medium to fine sand. Strata consisting of sand and lime mixture is in a loose state having some cavities. There are cavities in the stone masonry also because of washing out of material from the space in between. The loss of water in the boreholes, the low percentage recovery and caving of boreholes support the theory of existence of cavities in the substrata. The bottom most layer at 32.8 feet depth in borehole 1 consist of stiff yellowish clay with kankar, which can be assumed to be the natural deposit, but however the similar clay deposit in borehole 2 contain brick and stone pieces. This somehow creates a doubt to say conclusively that natural deposits without filled up material exist below 32.8 feet depth. A deeper borehole could throw exact light on the subject but in its absence, it may be a fair assumption that the clay with kankar strata starting at about 32 feet depth is perhaps the natural deposit at site. The presence of lime between 13 to 20 feet depth does suggest that upto these depths, the rubble masonry was laid in lime to support the minar. It is also probable that below this and above yellowish clay with kankar, stone filling with earth was done.

However, the details do suggest somewhat heterogeneous construction material and techniques, (figure 8).

The percentage core recovery in the two boreholes is rather low but the percentage recovery in borehole 1 is better than that in borehole 2. The reason is that borehole 1 being more inclined goes under the minar even upto some distance beyond its centre line while borehole 2 is located by its side. The material in borehole 1 has thus been subjected to higher stress which should result in better core recovery. Moreover, borehole 1 is towards the south-west direction in which the minar is tilting and because of the increased stress in this direction, the material will be comparatively more compact thereby resulting in better percentage core recovery.

TILT

There are no records available for the tilt of the minar prior to 1964 when survey of India registered the minar to be 25 inches out of plumb at the top towards the south-west direction. Since no previous records about the tilt of Qutb Minar are available, it is difficult to ascertain whether the tilt is totally or partially of recent origin or not. It is also difficult to state whether there was any tilt in the construction stage itself as the minar was built over a long span of time in stages. However, when the fourth and fifth storeys were rebuilt by Firoz Shah Tughlak in 1368, it appears that some tilt did exist and was apparently adjusted as is evident from the offset of the central shaft at the level of reconstruction. The heterogeneous composition and nature of the substructure and subsoil alongwith the deep depth of rock also suggest that there could be a possibility of early tilt in the minar, even during its construction because of differential settlements. Delhi also lies in seismic zone and occasional earthquake tremors are a common feature of this area. Qutb Minar had been subjected to several shocks of earthquakes since it was constructed and it is probable that shock loading of earthquakes may have resulted in the tilt of the minar because of readjustment of the heterogeneous supporting material. In 1964 several observation points had been marked on the projecting balconies of the minar for taking tilt observations.

The observations taken by Survey of India in 1976 for the tilt of Qutb Minar at different levels is shown in figure 9. It can be seen that the minar is 3.189 feet out of plumb at the top in the south-west direction. The tilt of the minar and the weathering agents have resulted in cracks in the minar (figure 10).

Central Building Research Institute took observations on Qutb Minar between 1976 to 1978. The crack width measurements were observed at several points with the help of deformeter after installing nylon pointers on two sides of the crack. Some of the cracks indicated continuous widening tendency suggesting immediate repair areas. Water level gauge and plumb assemblies were used for measuring tilt of Qutb Minar. For use of water level gauge, two water level pointers are fixed diametrically opposite to each other say one in S-W and the other in N-E

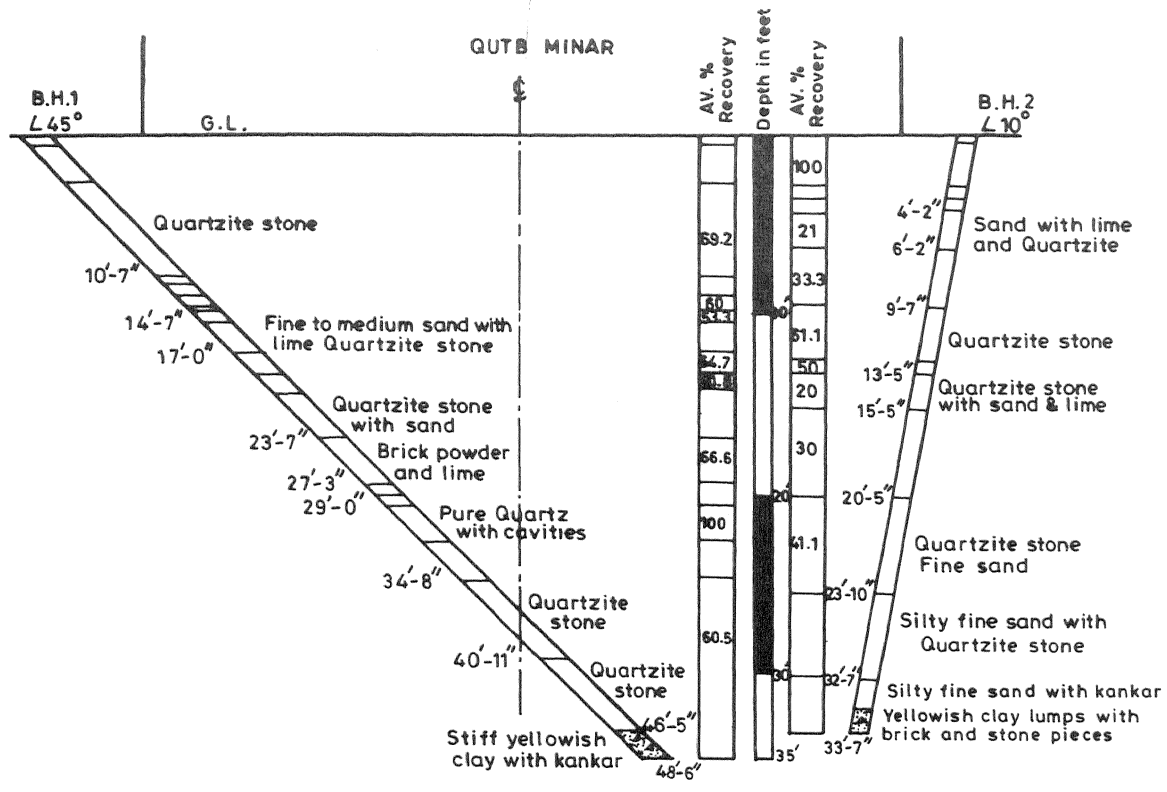


Fig.8: Borelogs at Qutb Minar

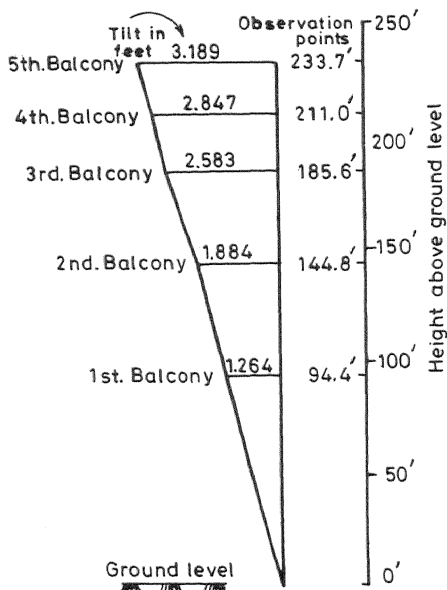


Fig.9: Tilts at Balcony levels (1976)

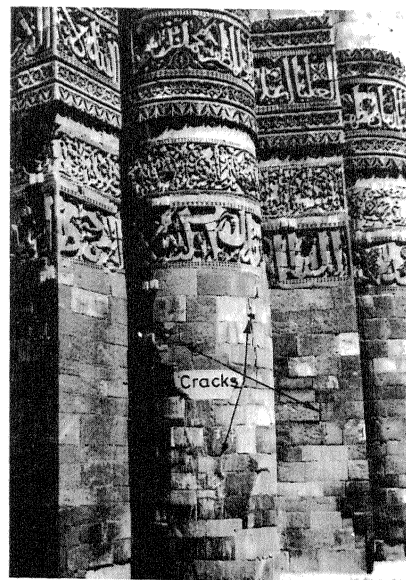


Fig.10: Cracks on outer face of Minar. Upper portion shows decorative bands.

direction. Successive readings taken over a period of time will enable to know the change in differential settlement and hence tilt. The plumb assemblies were suspended in stairway from the ceiling and their positions were noted on the footsteps. The observations taken by C.B.R.I. by both of these methods over a period mentioned earlier indicated that there is no further increase in the tilt of the minar indicating that it has stabilized after foundation strengthening by grouting in 1972.

STRENGTHENING OF FOUNDATION

In 1964, after the tilt in the minar was first observed, investigations into several aspects of the minar were undertaken. It was found that the substructure of the minar had open void spaces and the poor condition of its foundation could be the main cause of the tilt of this tower. The tilt though within safe limits at that time (25 inches) could increase and become dangerous. The differential settlement of the foundation was also the primary reason of some of the major cracks in the minar, the number and size of which was on the increase with time. With the increasing tilt the stresses in the soil could go beyond the ultimate bearing capacity and result in total collapse of the structure. In view of the above reasons, it was decided to strengthen the heterogeneous and weak foundation of the minar. The foundation was strengthened in 1972 by cement grouting which filled up all the voids in the foundation masonry thereby making it strong enough to withstand both static as well as earthquake loads in a better way, (figure 11).

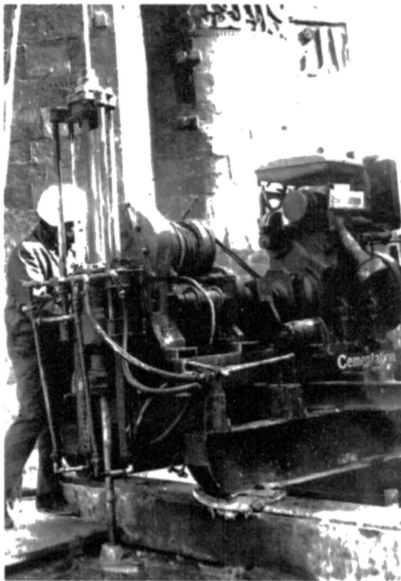


Fig.11: Grouting operation in progress at site (copy right A.S.I.)

The grouting also prevents any ingress of moisture into the substructure and the movement of soluble salts from the matrix. The grouting was done upto about 32 feet below ground surface. The grouting operation was performed in two phases. In phase I, a grout curtain was created by grouting holes along the periphery of the foundation platform making the grout curtain about 61 feet square in outside dimensions. Later the holes around the minar were grouted and then the holes in the four corners were taken up.

After the grout curtain was set to prevent cement grout to run out of the basal area, grouting in phase II, was done as per details given in figure 12 through radial holes from eastern and western sides taken through the ashlar facing of the platform. An overlapping of 5 feet on either side of the centerline of the minar was done.

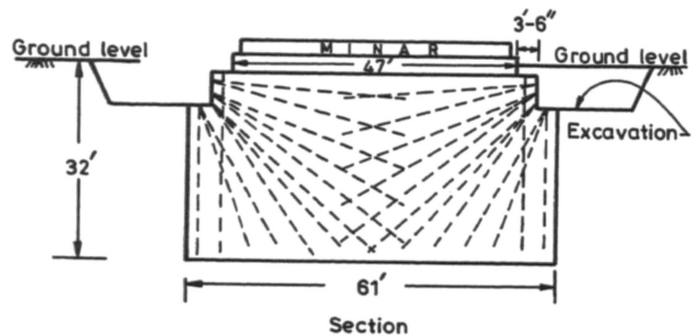


Fig.12:Sectional elevation showing radial grout holes in Qutb Minar foundation

The cement grout consisted of portland cement and clean water with a water - cement ratio varying between 4:1 to 1:1 . The grout holes had a diameter of 1 3/8 inches and the pressure varied between 5 to 15 p.s.i. Four upheaval gauges were installed around the minar to serve as a safeguard against upheaval of superstructure due to pressure grouting. Since the grouting was completed in 1972, it appears that there had been no further increase in the tilt of the minar & the foundation of this tower has stabilized. After the grouting, the minar can be taken to be supported on a grouted pedestal of 61 feet square going upto a depth of 32 feet below ground level.

ASSESSMENT

The weights of different storeys and their eccentricity at the respective C.G. were calculated to evaluate the moments. The maximum and minimum stresses were then determined in and under the foundation at different levels and are listed in Table 1.

Before the grouting was undertaken in 1972, the foundation had cavities in its substructure. The mortar and mud in the rubble masonry had partly disappeared and created voids in the matrix. The stress intensities as listed in Table 1 could have been dangerous under that condition at anytime, particularly during

TABLE 1: Maximum and minimum stresses at different levels.

Location	Maximum stress in S-W direction (t/sq.ft.)	Minimum stress in N-E direction (t/sq.ft.)
At 2 feet below plinth level	5.03	3.58
At 11'-6" below plinth level (probable bottom of acting foundation before grouting)	2.72	2.33
At bottom of foundation pedestal 32 feet below ground level (After grouting)	4.07	3.67

earthquakes. A structural rearrangement of sub-structure material could result in an increase of tilt or even collapse of superstructure. Now, after grouting the huge pedestal has started acting as a monolithic foundation which transfers the stresses to be carried safely by the substrata below. However, there is an urgent need of monitoring the tilt and the movements of this monument in the next several years to ascertain the long range effect of foundation underpinning.

REFERENCES:

- A.S.I. (1972), "Special Repairs to Qutb Minar Foundation by Consolidation Grouting".
- Brown, P., (1964), "Indian Architecture-Islamic Period".
- Carroll, David, (1972), "Taj Mahal".
- Minutes of the meetings of Expert Committee on Qutb Minar.
- Nath, R., (1977), "Agra and its Monumental Glory".
- Personal Communications - R.K.Bhandari, Dy Director, C.B.R.I., Roorkee.
- Personal Communications - R.Sengupta
- Personal Communications - Ratna Sengupta
- Survey of India, (1976). "Height and Tilt Observations of Qutb Minar".
- Sreenivasulu, V., Sengupta, R. and Bhandari, R.K., (1979), "Observations on Cracks and Tilt at Qutb Minar", International Symposium on Insitu Testing and Performance of Structures, Roorkee, pp.401-404.
- Trivedi, D.S., (1960), "Vishnudevaja", Annals (Bhandrakar, O.R.Institute), Vol.XL, pp240-261.