Taj Mahal – An Appraisal of Foundation Performance

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SYNOPSIS Because of severe restrictions placed by the National Authority, no authentic data on subsoil details below Taj Mahal - a protected monument - is available. For the first time, an attempt has been made to fill in gaps that exist in our knowledge of subsoil profile below the structure and present a plausible appraisal of foundation performance during the existence of the structure. Since details of foundations cited in literature on Taj Mahal really fall into the realms of architectural conjecture, in the present analysis, engineering intuition and judgement have gone into making certain premises regarding the probable type, dimensions and the depth of the existing foundations of Taj Mahal. These premises, complimented by borehole data and laboratory tests have enabled the assessment of the foundation performance to be made in as realistic a manner as is practically possible.

INTRODUCTION

The famed mausoleum Taj Mahal was built in Agra, India, by the great Mughal Emperor of Delhi, Shah Jahan to commemmorate his beautiful wife Mumtaz Mahal. The construction of the mausoleum began in 1632 and was completed in 1650. The structure is an architectural marvel and is remarkable for its stark simplicity and beauty of symmetry. Twenty thousand people were employed on the Taj Mahal for more than seventeen years and the structure is estimated to have cost about $ 45,000,000.

Taj Mahal is built on the bank of the river Yamuna and hence the construction of its foundation must have required special attention. It was the practice of the Mughal builders to support massive structures on masonry cylindrical foundations sunk into the soil at close intervals. Apparently, the terrace and the mausoleum building, as well as the minarets, rest on one firm, compact bed of masonry. There is, however, no record whatsoever, of the nature of subsoil strata that the construction engineers must have encountered when they carried out excavation for the foundations of Taj Mahal. Indeed, there is no clear evidence of even the types of foundation which were adopted and the depth upto which they were taken. The investigation was planned with a view to obtaining all soil data needed as inputs in the analysis of (a) performance of foundations of Taj Mahal, (b) the structure of Taj Mahal and (c) hydrological aspects, in the course of a collaborative project of great importance.

In order to achieve these objectives, it became necessary to make certain premises - well reasoned out - regarding the type, dimensions and the depth of the existing foundations of Taj Mahal. Further, it was necessary to extrapolate the subsoil strata details beneath the structure on the basis of bore log data from boreholes which had necessarily, to be located at some distance from the vicinity of the structure. The sequence of the subsoil strata and their boundaries were established upto the 'significant depth' - the depth upto which significant stresses would be transferred to the soil on account of loads from the structure and its foundation. A geotechnical investigation programme was planned and carried out to achieve this as well as to determine soil parameters like the shear strength and compressibility parameters, modulus of elasticity (E_s), Poisson's ratio (μ) and permeability (k) for each of the major strata beneath the foundation. The paper discusses only the aspects of foundation performance.

SOIL INVESTIGATION STRATEGY

Six boreholes were advanced, each upto a depth of about 40 m. It was realised that the depth of borehole ought to be greater if one had to include all significant soil layers. However, the subsoil strata details of one borehole near the northern boundary of Taj Mahal, advanced upto a depth of 100 m were available, courtesy CBRI, Roorkee, upto the significant depth of 100 m or so. It was proposed to advance, if necessary (in case of heterogeneity of strata), one or two boreholes to a greater depth. As it turned out, this became unnecessary since the subsoil data of the 100 m deep borehole matched well with those of other bore holes. Figure 1 shows the line plan of Taj Mahal complex with the locations of the boreholes B1 to B6 marked on it. Standard penetration tests were carried out at 1.5 m/3 m depth intervals in the boreholes. Representative and undisturbed samples were collected at regular intervals. The position of the ground water table was noted carefully. The samples were later tested in the laboratory for soil classification, natural water content determination,

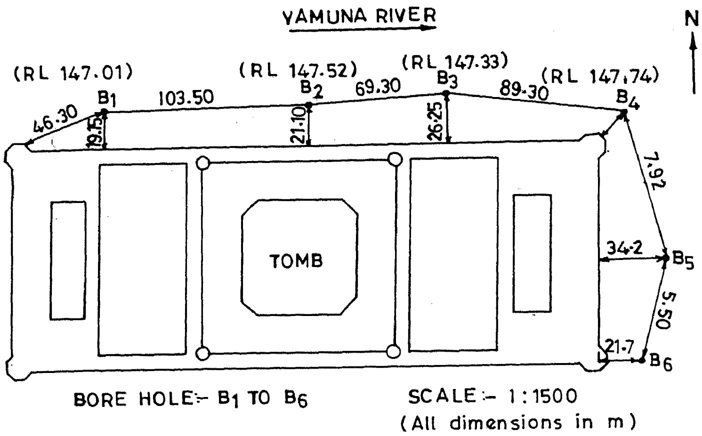

Fig. 1 Line Plan of Taj Mahal Complex with Borehole Locations

permeability tests, triaxial compression tests, unconfined compression tests and consolidation tests.

On the basis of soil strata encountered in different boreholes, two cross-sections of soil profiles, one along B1-B2-B3-B4 and the other along B4-B5-B6 were drawn. These are shown in Figs.2 and 3 respectively. It was observed that

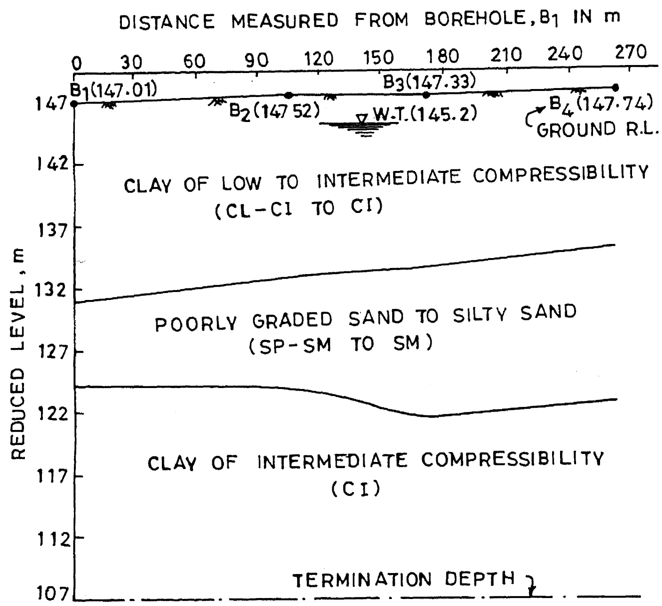

Fig. 2 Profile of Substrata Along B1-B2-B3-B4

there was no significant difference in the sequence of subsoil strata in the boreholes B1 to B6. The 100 m deep borehole was located close to B2 in Fig. 1.

SOIL STRATIFICATION

Comparison of the bore log data of the six 40 m deep boreholes with that of the 100 m

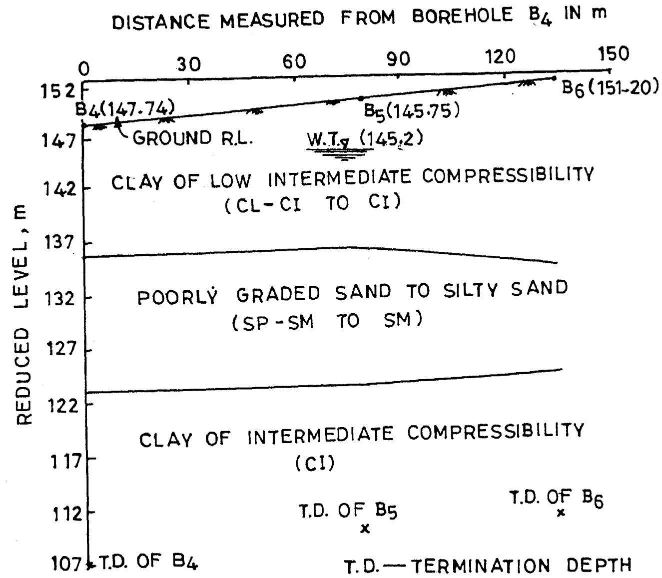

Fig. 3 Profile of Substrata Along B5-B6-B7

deep borehole showed a close agreement in the nature of subsoil details upto a depth of 40 m in all boreholes (making allowance, for change in RLs of different locations). The fairly homogeneous, well demarcated stratification also indicated that a projection of the same details of strata beneath the Taj Mahal would not be illogical.

On the basis of the seven borehole logs and plots of subsoil profiles along typical sections, the following sequential order of soil strata is projected for the substrata beneath the structure.

Reduced level (m)		Nature of Soil Stratum
From	To	
149.0	133.0	Clay of low to intermediate compressibility (CL-CI)-Stratum 1
133.0	123.8	Nonplastic sand to silty sand (SP-SM)-Stratum 2
123.8	60.2	Clay of intermediate compressibility (CI)-Stratum 3
At 60.2 m		Fine to medium grained quartzitic sand-stone

The clay stratum from RL 123.8 to 60.2 has two layers of silty sand sandwiched within it, each layer being about 5 m in thickness. The two layers exist at RL 98.0 and 77.0 m.

Ground water table was observed at an average RL of 145.2 m at the time of investigation (Nov-Dec. 1990).

PHYSICAL PROPERTIES AND ENGINEERING PARAMETERS

Extensive laboratory tests on several hundred soil samples collected from the boreholes yielded the following data:

	Stratum 1 (CL-CI)	Stratum 2 (SP-SM)	Stratum 3 (CI)
A. Physical properties			
(1) Unit weight	19.8 kN/m^3	20.0 kN/m^3	20.2 kN/m^3
(2) Natural water content, %	25.0	19.0	23.4
(3) Specific gravity of Solids	2.65	2.65	2.67
B. Engineering properties :			
(1) Undrained shear strength, c_u	45 kN/m^2	-	50 kN/m^2
(2) Angle of shearing resistance, ϕ	-	42^o	-
(3) Modulus of elasticity, E_s	-	55000 kN/m^2	50000 kN/m^2
(4) Poisson's ratio, μ	-	0.25	0.4
(5) Coefficient of permeability, k	$2x10^{-4}$ mm/s	$2x10^{-2}$ mm/s	$1.5x10^{-5}$ mm/s

ANALYSIS OF FOUNDATION PERFORMANCE

For the analysis of the performance of the foundations of Taj Mahal, it will be necessary to know the likely type, dimensions and the depth of the foundations as well as establish the boundaries of the subsoil strata beneath the structure.

Regarding the type of foundations, one has to rely on whatever historical and archaeological evidence that is available from published literature and the possible perceptions of the builders of that era. The flawless performance of Taj Mahal structure over the last three and a half centuries is a proof that the foundation must have been taken to a depth well below the maximum scour depth under maximum flood discharge of the Yamuna. Using a maximum flood discharge of 11304 m^3/s for Yamuna, an estimate of the maximum scour depth has been made. Computations indicate the RL of the maximum scour depth at approximately 135.0 m. Further, the foundation practice in those days was to avoid the sticky, clay soil for laying the foundations of monumental structures like Taj Mahal and to prefer a compact, nonplastic soil for the purpose. From the borehole logs, it has been established that the nonplastic silt/sand stratum which underlies the top clay stratum begins at an average RL of 133.0 m. The foundations of Taj Mahal may therefore be presumed to be taken upto RL 133.0 m. Further, for purposes of analysis, the foundation itself may be regarded as a solid, massive substructure behaving structurally like a raft. The width of the raft which governs the performance of the foundation, may be taken to be 110 m.

On the basis of borehole log data and the profile of the substrata, it is possible to define the boundaries of the substrata existing below Taj Mahal, to a reasonable degree of accuracy. Figure 4 shows the projected

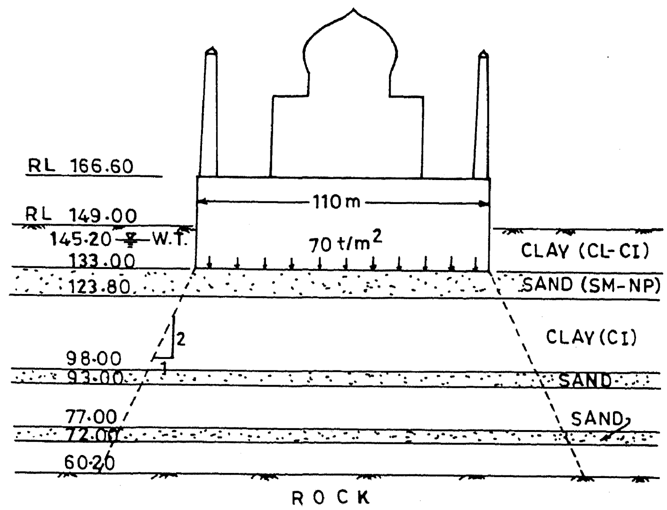

Fig. 4 Foundation-Soil System Used for Analysis

foundation-subsoil system which may be adopted for the foundation settlement analysis. The RL of the compact, rock stratum is taken as 60.2 m. Hence the foundation settlement can be expected to be limited to the deformation of the compressible stratum upto RL 60.2 m only. Deformation of the silty sand stratum is disregarded since most of this settlement would have taken place before the completion of the structure. The foundation settlement performance has been analysed in two parts:

(a) Evaluation of the magnitude of the ultimate settlement that the foundation of the structure is likely to experience.

(b) Estimation of the likely time-settlement relationship for the foundation.

On the basis of available evidence, it is surmised that the consolidation behaviour of only the clay soil (CI) described earlier as stratum 3, will be material. Hence no use will be made of the consolidation parameters of the clay stratum 1.

On the basis of consolidation test data on a number of samples taken froms stratum 3, the pressure -void ratio relationship, indicated in Table 1 below, is taken, on the basis of engineering judgement, as representative of the compressibility behaviour of the in situ clay stratum. Further, to facilitate the study of time-settlement relationship, a representative value of the coefficient of consolidation c_v

equal to $3x10^{-2}$ mm^2/s has been worked out for stratum 3. This value was chosen on the basis of several c_v values obtained from consolidation test data.

TABLE 1 - Pressure - Void Ratio Relationship

Pressure, $\bar{p}$ $kgf/cm^2 (x10^2 kN/m^2)$	Void ratio, e
0.0	0,523
0.25	0.500
0.5	0.484
1.0	0.461
2.0	0.440
4.0	0.411
8.0	0.374
16.0	0.380

Once the time-settlement relationship is projected, it will be possible to know what proportion of the total settlement has materialised at this point of time and how much more settlement if any, is likely to occur in future. This will help assess the future performance of the foundation.

For computing the ultimate settlement, the foundation soil is divided into a number of layers. The computations are carried out using a computer program. From the output, the ultimate settlement was obtained as 141 cm.

The estimation of the possible length of drainage path, H for the consolidating clay layer (CI) i.e., stratum 3, is a very vital factor in influencing the time-settlement relationship. A realistic value, considering the presence of sand/non plastic silt layers at different depths within the clay stratum, has to be assumed. With the help of soil details provided by the 100 m deep bore hole, the length of the drainage path has been assessed as 12.5 m.

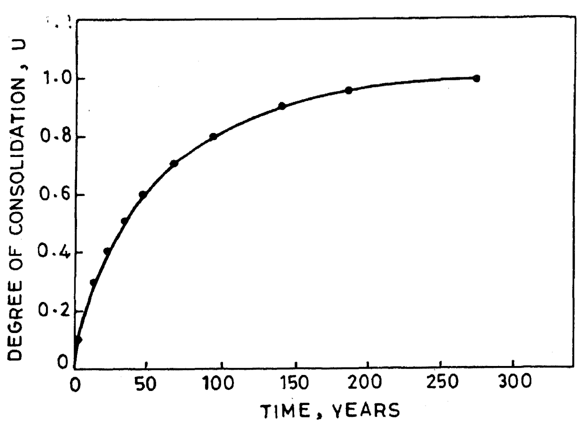

Fig. 5 Degree of Consolidation Versus Time

The degree of consolidation U versus time t relationship is shown in Fig. 5. It can be seen from Fig. 5 that 99 per cent of the ultimate settlement would have occured 294 years after the load was applied. The construction of Taj Mahal began in 1631 and was completed in 1653. If one works out the degree of consolidation corresponding to t = 350 years (approx.), it comes to about 99.4 per cent. In other words, 99.4 per cent of the ultimate settlement has already occured upto the present time and only about 0.6 per cent of the ultimate settlement, i.e. 0.006 x 141 cm or 0.87 cm settlement is expected to take place in future. The value is too small to affect in any way the performance of the foundation or the safety of the monument.

EFFECT OF IMPOUNDING WATER

The construction of a low level weir across the river Yamuna to impound water to create a permanent lake of water behind the Taj is envisaged. The pool level of impoundment is proposed to be RL 146.0 m. The effect of impounding water on foundation performance is also examined.

From the observations made during borehole tests, the present position of the natural ground water table is found to be at RL 145.2 m. During monsoon months, the water table is certainly bound to rise and it can be expected to reach an elevation higher than the proposed pool level. Considering that all the subsoil strata beneath the structure are already under submergence for a considerable period of time. it is quite obvious that the impounding of water in the river Yamuna is not going to alter the characteristics as found presently in the subsoil layers and consequently no allowance need be made for this while analysing the foundation performance.

CONCLUSIONS

For the first time, it has been possible to establish fairly conclusively the subsoil stratification beneath the 350 years old Taj Mahal and assess the performance of foundation of the structure with the help of a large number of field and laboratory test data.

The proposed impounding of water in the river Yamuna upto RL 146.0 m will have no influence on the behaviour of subsoil strata and hence on the performance of the foundations of Taj Mahal.

The future settlement of the foundation is likely to be insignificant and will present no problem to the stability of Taj Mahal.